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EFFECT OF CALCITE AND SILICA FUME ON COMPACTION AND CBR IN CLAY STABILIZATION

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ABSTRACT: This study evaluates the impact of calcite and silica fume on compaction properties and California Bearing Ratio (CBR) in clay stabilization. Clay from Cihampelas, West Bandung, was mixed with 5% calcite and silica fume at 6%, 8%, 10%, and 12%. The results show that silica fume significantly improved the CBR value. The original clay had an unsoaked CBR of 4.75% and a soaked value of 3.30%. With 12% silica fume, the unsoaked CBR increased to 7.15% and the soaked CBR to 5.80% after 7 days of compaction. The optimum moisture content (OMC) also increased from 20.50% to 23.50% with 12% silica fume. Fluctuations in maximum dry density (ɣ max) indicate structural changes in the soil. This study confirms that calcite and silica fume are effective in enhancing soil strength and stability, making them a viable solution for improving soil bearing capacity in construction. Further research is needed for long-term evaluation.

Keywords: Clay stabilization, Calcite, Silica fume, Compaction, California Bearing Ratio (CBR)

1. INTRODUCTION

Clay is one of the most challenging materials in geotechnical engineering due to its high compressibility, low strength, and susceptibility to changes in moisture content [1,2]. These unfavorable characteristics often lead to problems such as over settlement, reduced bearing capacity, and instability in construction projects [3,4]. As infrastructure construction and urbanization continue to expand, especially in areas with abundant clay deposits, the need for effective soil stabilization methods is becoming increasingly important [5]. Overcoming the inherent weaknesses of clay soils not only ensures structural stability but also reduces long-term maintenance costs, making soil stabilization a fundamental component of modern geotechnical engineering practices [6].

Various soil stabilization techniques have been developed over the years, ranging from mechanical methods, such as compaction and reinforcement, to chemical methods involving the addition of binders and additives [7,8]. Among the chemical approaches, the incorporation of cementitious materials has proven to be very effective in improving the engineering properties of clay soils [9]. However, traditional stabilizers such as lime and cement often pose environmental problems due to their high carbon footprint. This has prompted researchers to explore alternative materials that are sustainable and capable of achieving comparable or superior performance. In this context, calcite and silica fume have emerged as promising materials for soil stabilization.

In this context, calcite and silica fume have emerged as promising materials for soil stabilization. Calcite, which is chemically a calcium carbonate mineral, has an important role in soil stabilization, especially in improving microstructure stability [10], Calcite is known for its ability to improve soil structure by increasing particle bonding [11,12]. Calcite provides a stable matrix that reduces plasticity and increases strength [13]. The addition of calcite to clay soil triggers a chemical reaction that reduces plasticity and increases density through the binding of soil particles [14]. In addition, calcite also plays a role in reducing the development of clay soil due to the expansion of active clay minerals. Previous studies have shown that the addition of calcite can significantly increase the shear strength and bearing capacity of soils, thus making it an effective additive in clay soil stabilization [7]. However, the effectiveness of calcite tends to depend on interactions with other soil minerals, opening up opportunities to combine calcite with other additives, such as pozzolanic materials, to maximize its benefits.

On the other hand, Silica fume is a by-product of the silicon and ferrosilicon industry that has a high amorphous silica content [15,16], with a very small particle size and large surface area [17]. These characteristics make silica fume a highly reactive pozzolanic material [18]. When added to soil, silica fume interacts with calcium hydroxide resulting from chemical stabilization [19], forming calcium silicate hydrate (CSH) [20]. This product not only increases soil strength and density [21], but also provides resistance to extreme environmental conditions. In addition, silica fume is known to increase soil density by filling the spaces between particles, resulting in soils with a tighter and firmer structure [22]. Several studies have shown that the addition of silica fume can increase California Bearing Ratio (CBR) values, resistance to loading, and reduce the risk of deformation in clay soils [23]. The combination of these two materials has a potential synergistic effect, which can surpass the benefits of using each material separately [13].

Stabilization of clay soils is an important aspect of geotechnical engineering, especially in areas with soils characterized by high plasticity, low bearing capacity, and sensitivity to changes in moisture content [24,25]. These issues often pose challenges in construction projects, such as foundation failure, structural cracking, and excessive settlement. Various techniques have been applied to overcome these challenges [26], which can be broadly divided into traditional and modern approaches. Traditional approaches, such as mechanical compaction, the addition of granular materials, and the use of geosynthetic materials, offer relatively simple solutions. However, these techniques are often limited to improving the physical properties of the soil without providing significant changes to its chemical and structural properties. On the other hand, modern approaches emphasize the use of additives, such as lime, cement, and pozzolanic materials, which are capable of improving the overall soil properties through chemical and physical processes [27].

Although there have been many studies on the use of calcite and silica fume separately, research on the combination of these two materials in clay stabilization is still very limited. Most studies focus on the use of one of the two materials without exploring the potential synergies that can occur when they are combined. In addition, the effect of varying silica fume content on the compaction properties and CBR values of clay soils has not been systematically investigated in the context of using calcite as a locking agent. This research aims to fill this gap by evaluating the effect of the combination of calcite. This research is expected to provide a deeper understanding of the stabilization mechanism involving these two materials, and offer innovative and sustainable solutions to geotechnical problems in areas with clay soils.

This research focuses on the stabilization of clay soil from Cihampelas, West Bandung Regency, using a combination of calcite and silica fume. The calcite content was set at 5%, while silica fume was varied at 6%, 8%, 10%, and 12% were selected based on preliminary findings from related studies that indicated these levels would enhance soil stabilization properties without causing excessive changes to the soil's structural integrity [15,28,29]. These percentages were intended to provide a range of data to evaluate the gradual effect of silica fume on compaction properties and the California Bearing Ratio (CBR). Further studies may explore the potential of using silica fume concentrations beyond 12% to fine-tune the stabilization process.

2. RESEARCH SIGNIFICANCE

Stabilization of clay soils is a major challenge in geotechnical engineering due to their high plasticity, low bearing capacity and moisture sensitivity. This research is particularly important as it investigates the use of a combined calcite and silica fume as a more environmentally friendly alternative to conventional stabilizers like cement and lime. Although previous research was limited, the results showed significant improvements in soil density and bearing capacity. This new approach provides a sustainable and effective solution to improve the stabilizability and durability of clay soils in construction, especially in areas where traditional methods can pose environmental and economic problems.

3. MATERIALS AND METHODS

3.1 Materials

The clay soil used in this study was taken from Cihampelas Subdistrict, West Bandung Regency. The soil samples were characterized through laboratory testing to determine their physical properties, such as plasticity, particle size distribution, specific gravity, and Atterberg limits. The characterization results showed that the soil is a clay soil with high plasticity, so it is necessary to improve the technical properties to meet construction needs.

The stabilization materials used were calcite and silica fume. Calcite is a high purity calcium carbonate powder, which was chosen for its ability to increase cohesion between soil particles. The calcite content was locked at 5% of the total dry weight of the sample to ensure the consistency of the effect. Silica fume, which is a pozzolanic material with an amorphous silica content of more than 85%, was used at variations of 6%, 8%, 10%, and 12%. Silica fume was selected due to its ability to enhance the chemical reaction of soil stabilization through the formation of calcium silicate hydrate (CSH) [30], these two additives are expected to have a synergistic effect in improving the density and bearing capacity of the soil.

3.2 Flow of Research

This research was conducted systematically, starting from material preparation, laboratory testing, to data analysis. The main stages included characterization of clay, mixing of stabilization materials (calcite and silica fume), compaction testing (Standard Proctor), and California Bearing Ratio (CBR) testing with various curing periods. The entire research process is documented in a flow chart that provides a detailed explanation of the methodology flow as shown in Figure 1.

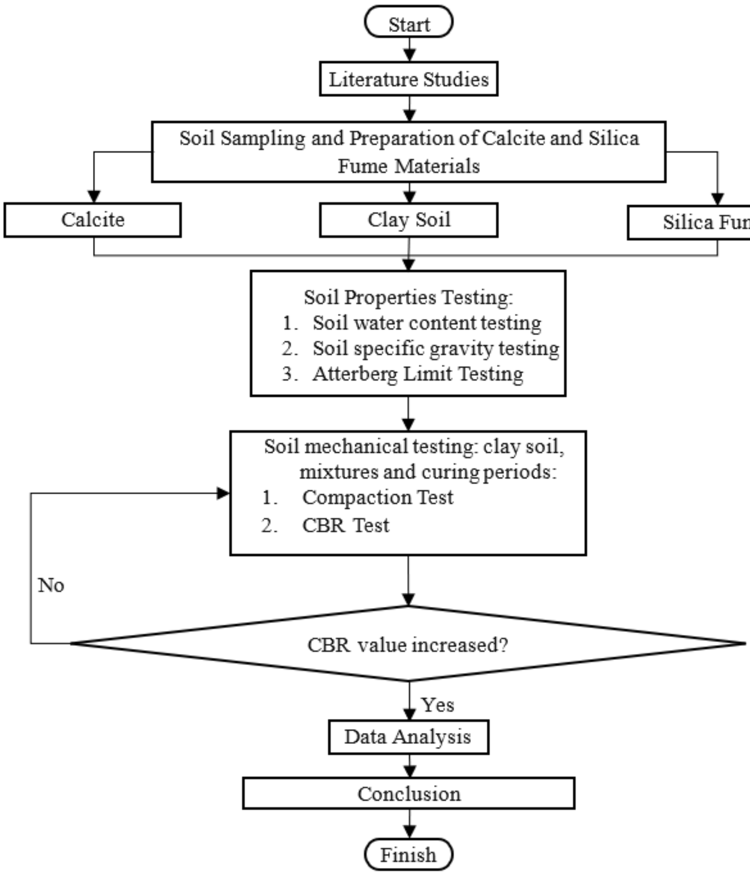

Fig. 1 Research Flow Chart

3.3 Research Methodology

3.3.1 Preparation of Soil Mixtures and Stabilizers

The dried and crushed clay was sieved with a 4.75 mm sieve to ensure sample uniformity. The mixture was prepared by adding 5% calcite to the soil, followed by silica fume at various levels (6%, 8%, 10%, and 12%). The process of mixing the soil with silica fume and calcite was done manually. Mixing was done with the aim of ensuring the additives were evenly mixed with the soil. Although hand mixing requires more precision, the distribution of silica fume and calcite in the soil mixture can be ensured to be quite homogeneous. This process involves carefully mixing the crushed soil with the silica fume and calcite, so that all the ingredients are evenly and consistently mixed.

Once the ingredients are evenly mixed, water is then added little by little to the mixture to achieve the desired moisture. The addition of water was done gradually to ensure the mixture remained homogeneous and not too wet, thus facilitating the subsequent compacting process.

Although hand mixing was adequate for this study, mechanical mixing can be more efficient in ensuring a more uniform and consistent distribution. Therefore, the use of a mechanical mixing device is recommended for further research to obtain more consistent results and reduce potential variations in the mix., as can be seen in Figure 2.

Fig. 2 The Mixing Process

3.3.2 Compaction Test

Compaction tests were conducted in accordance with ASTM D698 to determine the OMC and MDD of each mix. This test aims to evaluate the optimum density that can be achieved, which becomes a reference for further CBR testing.

3.3.3 California Bearing Ratio (CBR)

CBR testing was conducted on samples

compacted to optimum moisture content. Samples were tested after 0 and 7 days of curing to evaluate the effect of time on soil bearing capacity. In soaked CBR testing, based on ASTM D1883, soil samples are soaked in water for 4 days with increasing loads to simulate saturation conditions in the field. After the soaking period, a penetration test is conducted to determine the CBR value at the fully saturated condition. This approach ensures a realistic assessment of soil performance under wet conditions. CBR values were measured based on the ratio of penetration load to standard, with the results showing the effectiveness of the combination of calcite and silica fume. CBR test can be seen in Figure 3.

Fig. 3 CBR Testing

4 RESULT AND DISCUSSION

4.1 Compaction Result

The soil property index test was carried out to classify and thoroughly identify the type of soil used in this study. This test involves evaluating the physical and mechanical properties of the soil to understand its characteristics in detail. Physical property testing includes measuring the specific gravity of the soil and the Atterberg limits, which provide important information about the particle size distribution and consistency of the soil. In addition, the mechanical properties of the soil are assessed through compaction tests and the California Bearing Ratio (CBR) test, which aims to understand the behavior and stability of soft clay soil in various conditions. These tests were carried out systematically on soft clay soil samples, and the results are summarized in Table 1 and Table 2, which provide a comprehensive basis for further analysis and interpretation in this study.

Table 1. Index Properties of Soft Clay Soil

No	Index Properties	Sym.	Unit	Value	Std. Spec.
1	Water Content	ω	%	41.48	ASTM D2216
2	Specific Gravity	Gs	kN/m^3	25.40	ASTM D854
3	Weight of Content	γ	kN/m^3	18.60	ASTM D7263
4	Dry Weight	γd	kN/m^3	13.14	ASTM D2216
5	Atterberg Limit	%			ASTM D4318
	- Plastic Limit	PL	%	30	
	- Liquid Limit	LL	%	59	
	- Plasticity Index	PI	%	29	

Table 2. Mechanical Properties of the Soft clay

No	Mechanical Properties	Sym.	Unit	Value	Std. Spec.
1	Compaction	W opt	%	20.50	ASTM D1557
2	CBR		%		ASTM D1883
	-Unsoaked		%	4.75	
	-Soaked		%	3.3	

The Table 3 and Fig. 4 above shows the results of compaction testing on clay soil stabilized with a mixture of calcite at 5% and silica fume (SF) with varying levels, namely 6%, 8%, 10%, and 12%. The clay soil used in this study came from Cihampelas District, West Bandung Regency. The main parameters observed were optimum moisture content (W opt) and maximum dry density (ɣ max), which describe the physical properties of the soil after stabilization.

Table 3. Compaction Result

No	Soil & Mixtures	W opt %	ɣ max kN/m^3
1	Soft clay	20.50	12.92
2	Soil + Calcite 5% + SF 6%	20.08	14.16
3	Soil + Calcite 5% + SF 8%	21.00	13.18
4	Soil + Calcite 5% + SF 10%	22.95	13.04
5	Soil + Calcite 5% + SF 12%	23.50	12.88

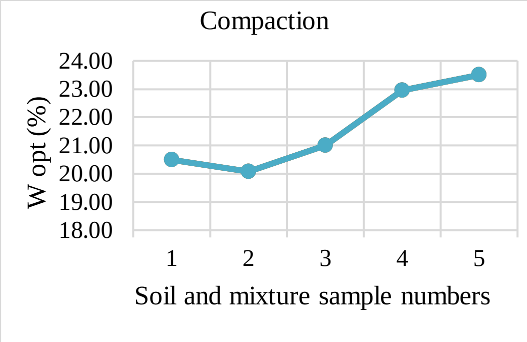

Fig. 4 W opt of Compaction

Based on the data in the table, it can be seen that the optimum moisture content (W opt) increases with increasing silica fume content, from 20.50% in the original clay to 23.50% in the mixture with 12% SF. This increase in optimum moisture content can be caused by the nature of silica fume which is very fine and easily absorbs water [31]. As a result, the soil mixture requires more water to reach the maximum density.

Meanwhile, the maximum dry density (ɣ max) value showed fluctuations. At 6% SF content, the pd max value increases to 14.16 kN/m³, but at higher SF content, this value tends to decrease. This decrease is not due to the weakening of the mechanical properties of the soil, but rather because calcite and silica fume have a lower density than the original clay. In addition, the chemical interaction between silica fume and soil results in a stiffer soil structure, despite the reduced dry density.

These results indicate that the addition of calcite and silica fume affects the physical parameters of clay soils, especially in terms of optimum moisture content and maximum dry density. The increase in optimum moisture content and fluctuations in maximum dry density illustrate the balance between the properties of the additives and the characteristics of the original clay soil [32]. Overall, the mixture resulted in a more stable soil with improved mechanical properties for geotechnical engineering purposes. This proves the effectiveness of using calcite and silica fume as clay stabilization materials.

4.2 California Bearing Ratio (CBR) Analysis

The Table 4 of the California Bearing Ratio (CBR) test on stabilized clay soils using a mixture of calcite and silica fume show a significant increase in the bearing capacity of the soil. In unstabilized clay soils, the CBR reached only 4.75% and 3.30% in non-soaked and soaked conditions, respectively. However, with the addition of 5% calcite and silica fume (SF) at levels of 6%, 8%, 10% and 12%, the CBR of the soil increased consistently with curing time.

Table 4. CBR Result

No	Soil & Mixtures	Curing Time (Days)	CBR (%)	
			Unsoaked	Soaked
1	Soft clay	-	4.75	3.30
2	Soil + Calcite 5% + SF 6%	0	5.04	3.69
		7	5.25	3.90
3	Soil + Calcite 5% + SF 8%	0	5.20	3.90
		7	6.00	4.65
4	Soil + Calcite 5% + SF 10%	0	5.82	4.40
		7	6.25	4.90
5	Soil + Calcite 5% + SF 12%	0	5.85	4.80
		7	7.15	5.80

Mixtures with higher levels of SF, particularly 12%, gave the best results, with an unsoaked CBR of 7.15% and a soaked CBR of 5.80% after 7 days of compaction. This increase shows that silica fume plays an important role in increasing the stability and strength of clay soils in both dry and wet conditions. The addition of silica fume, which acts as a binder [30], effectively increases the strength of clay soils that initially have a low bearing capacity [22,33], making them more suitable for construction applications such as roads or foundations [34]. This CBR analysis provides a clear picture of the effectiveness of a mixture of calcite and silica fume as a soil stabilizer, with optimum curing time and higher SF levels showing better performance.

4.3 Comparative Analysis

The performance of the proposed stabilization method, which combines calcite and silica fume, is compared with traditional techniques such as the use of cement or lime. The results show that the combination of calcite and silica fume produces a more significant improvement in both compaction properties and CBR (California Bearing Ratio) values compared to conventional methods. For example, traditional soil stabilization methods such as lime or cement do increase the CBR value, but not as much as observed in the calcite-silica fume mixture. The significant increase in CBR value in unsoaked and soaked conditions indicates the better stabilization potential of the proposed method.

Although traditional stabilizer materials such as cement can significantly increase soil strength, the environmental impact of its production is still a major concern due to the high carbon emissions of the cement production process. In contrast, calcite and silica fume are more environmentally friendly, offering greener alternatives with equivalent or better performance in improving the mechanical properties of soil. In addition, the addition of silica fume significantly increases the soil's resistance to moisture, as seen from the increase in CBR value in wet conditions.

The optimal percentage of silica fume was found to be 12%, which resulted in the best improvement in compaction and CBR characteristics, indicating that higher levels of silica fume are more conducive to the chemical reactions necessary to increase soil strength and stability. These findings indicate that the combination of calcite and silica fume can be considered an environmentally friendly and effective soil stabilization alternative compared to conventional techniques.

4.4 Discussion

The observed improvement in soil properties due to the addition of calcite and silica fume can be explained by several factors. Calcite, with its ability to bind soil particles, plays an important role in reducing plasticity and increasing soil cohesion. The formation of calcium carbonate bonds between soil particles produces a denser structure, which increases soil strength. Meanwhile, silica fume, with a highly reactive silica content and very small particle size, further increases soil strength through a pozzolanic reaction with the calcium hydroxide found in the soil, producing calcium silicate hydrate (CSH). This product not only increases strength but also the soil's resistance to environmental stresses, such as changes in humidity.

The interaction between calcite and silica fume creates a synergistic effect, where these two materials complement each other in increasing soil compaction and carrying capacity more effectively than using only one of the materials. The combination of these two materials produces a more durable and stable soil matrix, making it suitable for construction applications such as roads, foundations, and backfilling.

In addition, the increase in optimum moisture content (OMC) with higher additions of silica fume, as seen in the compaction test, shows that the very fine particle size of silica fume and its high absorbency require more water to achieve the desired compaction. Although the moisture content increases, the maximum dry density value (ɣ max) shows little fluctuation, which indicates a change in soil structure due to chemical interactions between additives and soil particles. However, these changes do not significantly weaken the mechanical properties of the soil, but rather increase the overall stability of the soil.

5. CONCLUSIONS

This study shows that the combination of calcite and silica fume significantly improves the compaction characteristics and California Bearing Ratio (CBR) value of clay soil. Based on the CBR tests conducted, the optimum silica fume content was 12%, where the CBR value was highest. This indicates that at this percentage, the pozzolanic reaction and particle bonding reaches an optimum level, increasing the bearing capacity of the soil while maintaining a balanced moisture content. The soft clay soil had a CBR value of 4.75% (unsoaked) and 3.30% (soaked). With the addition of 12% silica fume, the CBR value increases to 7.15% (unsoaked) and 5.80% (soaked) after 7 days of compaction. This increase shows that silica fume plays an important role in increasing the bearing capacity of the soil, both in dry and wet conditions. In addition, the compaction test results show an increase in the optimum moisture content (OMC) from 20.50% to 23.50% in the mixture with 12% silica fume, as well as fluctuations in the maximum dry density value (ɣ max) which reflects changes in soil structure due to the interaction of stabilization materials with the soil.

This stabilization method has great potential for application in construction projects, especially in areas with high clay content, where the soil tends to be unstable and has a low bearing capacity. The success of this method in improving the mechanical properties of the soil makes it an effective solution for increasing soil stability in road construction, foundations, and other projects. Further research is needed to conduct large-scale validation in the field to confirm its effectiveness in more varied conditions, as well as to assess the performance and durability of stabilized soil in the long term, especially in dealing with variations in load and climate change

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7. REFERENCES

[1] Sakr M, El-Sawwaf M, Azzam W, El-Disouky E. Improvement of shear strength and compressibility of soft clay stabilized with lime columns. Innovative Infrastructure Solutions 2021;6:1. https://doi.org/10.1007/s41062-021-00509-w.

[2] Arifin YF, Rahmah RF. Stabilization of Soft Clay from Bukit Rawi using Portland Composite Cement. IOP Conf Ser Earth Environ Sci, vol. 999, IOP Publishing Ltd; 2022, p. 1–7. https://doi.org/10.1088/1755-1315/999/1/012027.

[3] Zhang L, Li Y, Wei X, Liang X, Zhang J, Li X. Unconfined Compressive Strength of Cement-Stabilized Qiantang River Silty Clay. Materials 2024;17:1–16. https://doi.org/10.3390/ma17051082.

[4] Waruwu A, Purba SM, Wijaya NY, Sumantri NA, Pangemanan IL. The Performance Of Soil Stabilization With Marble Ash In Physical Model Tests In The Laboratory. International Journal of GEOMATE 2024;27:49–56. https://doi.org/10.21660/2024.124.4647.

[5] Morissa M, Syahril S. Effect of addition of palm shell ash and asphalt emulsion for bearing capacity on clay soils. IOP Conf Ser Mater Sci Eng, vol. 1098, IOP Publishing; 2021, p. 1–6. https://doi.org/10.1088/1757-899x/1098/2/022059.

[6] Sánchez-Garrido AJ, Navarro IJ, Yepes V. Evaluating the sustainability of soil improvement techniques in foundation substructures. J Clean Prod 2022;351:1–20. https://doi.org/10.1016/j.jclepro.2022.131463.

[7] Syahril, Purba DA, Sagala SD, Prayogo RDRB. Improvement of Clay Properties with Calcite and Silica Fume: Shear and Unconfined Compressive Strength Focus. Journal of Hunan University (Natural Sciences） 2025;52:47–57. https://doi.org/10.55463/issn.1674-2974.52.1.5.

[8] Yeganeh RA, Teymür B. Effect of Magnesium Chloride Solution as an Antifreeze Agent in Clay Stabilization during Freeze-Thaw Cycles. Applied Sciences (Switzerland) 2024;14:1–18. https://doi.org/10.3390/app14104140.

[9] Ahmed A, El-Emam M, Ahmad N, Attom M. Stabilization of Pavement Subgrade Clay Soil Using Sugarcane Ash and Lime. Geosciences (Switzerland) 2024;14:1–20. https://doi.org/10.3390/geosciences14060151.

[10] Bargi MM, Rasouli GO, Tajdini M. An investigation on the effects of adding nano-Sio2particles and silica fume with different specific surface areas on the physical and mechanical parameters of soil-cement materials. Civil Engineering Infrastructures Journal 2021;54:93–109. https://doi.org/10.22059/CEIJ.2021.291231.1619.

[11] Shah SHA, Sajjad RU, Javed A, Habib U, Ahmad F, Mohamed A. Geotechnical investigation and stabilization of soils through limestone powder at Abbottabad, Khyber-Pakhtunkhwa, Pakistan: a cost effective and sustainable approach. Front Earth Sci (Lausanne) 2023;11:1–19. https://doi.org/10.3389/feart.2023.1243975.

[12] Jiang P, Zhou L, Zhang W, Wang W, Li N. Unconfined Compressive Strength and Splitting Tensile Strength of Lime Soil Modified by Nano Clay and Polypropylene Fiber. Crystals (Basel) 2022;12:1–15. https://doi.org/10.3390/cryst12020285.

[13] Harish DrK, Reddy ChS, Yuvaraju A, Prabhudeva P, Hemalatha K, Bramham V, Srinivas P. A Study On Stabilization of Soils by Using Egg Shell Powder. International Journal of Innovative Research in Engineering and Management 2023;10:96–8. https://doi.org/10.55524/ijirem.2023.10.2.17.

[14] Mahardika IG, Ricci, Suhendra A, Juliastuti, Pahlevi C. The effect of additional limestone on expansive soil at Summarecon Emerald East Karawang. IOP Conf Ser Earth Environ Sci, vol. 998, IOP Publishing; 2022, p. 1–11. https://doi.org/10.1088/1755-1315/998/1/012018.

[15] Alrubaye AJ, Hasan M, Fattah MY. Improving Geotechnical Characteristics of Kaolin Soil Using Silica Fume and Lime. Special Topics & Reviews in Porous Media-An International Journal 2016;7:77–85.

[16] Fattah MY, Al-Saidi ÀA, Jaber MM. Characteristics of clays stabilized with lime-silica fume mix. Italian Journal of Geosciences 2015;134:104–13. https://doi.org/10.3301/IJG.2014.36.

[17] S NGB, S SM, K N. Experimental investigation and stabilization of Black Cotton Soil using Micro Silica and Renolith. International Research Journal of Engineering and Technology 2020;07:1731–5.

[18] Öztürk O, Türköz M. Effect of silica fume on the undrained strength parameters of dispersive soils. Turkish Journal of Engineering 2022;6:293–9. https://doi.org/10.31127/tuje.1001413.

[19] Munirwan RP, Taha MR, Taib AM, Munirwansyah M. Shear Strength Improvement of Clay Soil Stabilized by Coffee Husk Ash. Applied Sciences (Switzerland) 2022;12:1–14. https://doi.org/10.3390/app12115542.

[20] Abd-Allah OA, Awn SHA, Zehawi RN. Improvement of Soft Clay Soil Using Different Types of Additives. IOP Conf Ser Earth Environ Sci, vol. 856, IOP Publishing Ltd; 2021, p. 1. https://doi.org/10.1088/1755-1315/856/1/012010.

[21] Yang Q, Du C, Zhang J, Yang G. Influence of Silica Fume and Additives on Unconfined Compressive Strength of Cement-Stabilized Marine Soft Clay. Journal of Materials in Civil Engineering 2020;32:1–14.

https://doi.org/10.1061/(asce)mt.1943-5533.0003010.

[22] Ali NA, Karkush MO. Improvement of Unconfined Compressive Strength of Soft Clay using Microbial Calcite Precipitates. Journal of Engineering 2021;27:67–75. https://doi.org/10.31026/j.eng.2021.03.05.

[23] AL-Soudany K. Improvement Of Expansive Soil By Using Silica Fume. Kufa Journal of Engineering 2018;9:222–39. https://doi.org/10.30572/2018/kje/090115.

[24] Karumanchi M, Avula G, Pangi R, Sirigiri S. Improvement of consistency limits, specific gravities, and permeability characteristics of soft soil with nanomaterial: Nanoclay. Mater Today Proc, vol. 33, Elsevier Ltd; 2020, p. 232–8. https://doi.org/10.1016/j.matpr.2020.03.832.

[25] Edora AB, Adajar MAQ. Strength And Permeability Characteristics Of Expansive Soil With Gypsum And Rice Husk Ash. International Journal of GEOMATE 2021;21:28–34. https://doi.org/10.21660/2021.88.gxi251.

[26] Tan JF, Adajar MAQ. Recycled Gypsum And Rice Husk Ash As Additives In The Stabilization Of Expansive Soil. International Journal of GEOMATE 2020;17:197–202. https://doi.org/10.21660/2020.70.9201.

[27] Muntaha M, Fitrie RHA, Wahyuni F, Tajunnisa Y. The Use Of Alkaline Activators With High Calcium Fly Ash As Soft Clay Stabilization Materials. International Journal of GEOMATE 2023;25:9–17. https://doi.org/10.21660/2023.109.3286.

[28] Al-Gharbawi ASA, Najemalden AM, Fattah MY. Expansive Soil Stabilization with Lime, Cement, and Silica Fume. Applied Sciences (Switzerland) 2023;13:1–15. https://doi.org/10.3390/app13010436.

[29] Fattah MY, Joni HH, Al-Dulaimy ASA. Strength characteristics of dune sand stabilized with lime-silica fume mix. International Journal of Pavement Engineering 2018;19:874–82. https://doi.org/10.1080/10298436.2016.1215687.

[30] Phanikumar BR, Raju ER. Compaction and strength characteristics of an expansive clay stabilised with lime sludge and cement. Soils and Foundations 2020;60:129–38. https://doi.org/10.1016/j.sandf.2020.01.007.

[31] Barman D, Dash SK. Stabilization of expansive soils using chemical additives: A review. Journal of Rock Mechanics and Geotechnical Engineering 2022;14:1319–42. https://doi.org/10.1016/j.jrmge.2022.02.011.

[32] Zemouli S, Gouider N, Melais Fatma Z, Wissem I. Cement kiln dust and polypropylene fiber in expansive clay improvement. Studies In Engineering And Exact Sciences 2024;5:1771–92. https://doi.org/10.54021/seesv5n1-089.

[33] Hastuty IP, Roesyanto, Stephanes D. The use of bottom ash and limestone as soil stabilization material based on unconfined compression test. IOP Conf Ser Mater Sci Eng, vol. 801, Institute of Physics Publishing; 2020, p. 1–7. https://doi.org/10.1088/1757-899X/801/1/012009.

[34] Nugroho SA, Wibisono G, Ongko A, Mauliza AZ. Effects of High Plasticity and Expansive Clay Stabilization with Lime on UCS Testing in Several Conditions. Journal of the Civil Engineering Forum 2021;7:147–54. https://doi.org/10.22146/jcef.59438.