

RESEARCH ARTICLE

The Effect of Limestone Variations on the Compressive Strength of Clay Soil Stabilized with Pumice Microsilica and Aluminum Hydroxide

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Abstract

The pozzolanic reaction is a chemical interaction involving calcium hydroxide, silica, and alumina that contributes to the chemical stabilization of soil. An optimized proportion of these three components can yield greater improvements in soil strength compared to the use of a single stabilizing material. This research examines the additional effect of limestone as a calcium source on clay soil stabilized with pumice-based microsilica and hydroxide aluminate. The testing of soil properties in this research follows the American Society for Testing Materials (ASTM) guidelines. The stabilization materials used include pumice, hydroxide aluminate, and limestone. The mechanical behavior of the blend of these three minerals is determined from the findings of the unconfined compressive strength tests, using cylindrical test samples measuring 35 mm in diameter and 70 mm in height. Variations in the addition of lime used to form the mixed matrix were 2%, 4%, and 6% by weight of dry soil. Laboratory test results showed a very significant increase in unconfined compressive strength (q_u) compared to natural soil or soil stabilized only with silica and alumina. The optimum value for lime addition in this mixture was 4%, which resulted in a q_u value of 52.48 kg/cm².

Keywords: Soil stabilization, limestone, pumice sand, aluminum hydroxide

1. Introduction

Road infrastructure development often faces the problem of soft soil due to its low bearing capacity. This is due to the properties of soft soil, which has high compressibility, is susceptible to expansion and shrinkage, has high water absorption, and is impermeable (Das, 2019). Low soil bearing capacity will certainly affect the stability of the infrastructure standing on the soil, resulting in excessive deformation when loaded. The distribution of soft soil in Indonesia reaches 10% of the land area (Kimpraswil, 2002), thus requiring special attention in planning to reduce the failure of the structures to be built.

Material engineering methods for soft soils are increasingly evolving along with advances in material measurement technology and growing awareness of sustainable and environmentally friendly development. Currently, the use of conventional binders, such as cement, activated lime, and other chemicals, has shown positive results in increasing soil bearing capacity. However, these materials are considered uneconomical for large-scale projects. Furthermore, the limestone calcination process produces significant greenhouse gas emissions (Abdulkareem, et al., 2019). Meanwhile, (Mahasenan, et al., 2003) noted that producing 1,000 kg of cement releases 900 kg of CO₂ into the atmosphere. In other words, the use of conventional materials is more expensive and less environmentally friendly.

The development of alternative binding materials to reduce or replace conventional materials has become a challenge in environmentally friendly material engineering, including the use of natural materials or industrial waste. The use of these materials as binders is based on their pozzolanic reaction properties (Menéndez, et al., 2020; Bayiha, et al., 20223). Pozzolanic materials contain silica or alumina-silica compounds and have little to no cementing properties. However, in a finer form and with the addition of water, they react with calcium hydroxide [Ca(OH)₂] to form cement-like compounds (Dodson, 1990; Gómez & F. Rojas, 2013).

The pozzolanic reaction is a reaction between calcium hydroxide (Ca(OH)₂) produced by the hydration of cement and pozzolanic materials containing silica and/or alumina in the presence of water (McCarthy & Dyer, 2019), which produces hydrated compounds such as C-S-H (calcium silicate hydrate) as well as C-A-H or C-A-S-H, which have cementitious properties; in this reaction, silica plays a primary role in forming C-S-H, which is the most dominant phase and is responsible for mechanical strength and microstructural density (Raveendran & Vasughi, 2024), while aluminate plays a more complex role by contributing to the formation of additional hydrated phases such as C-A-H and C-A-S-H, accelerating the initial reaction through the formation of metastable phases (e.g., CAH₁₀ and C₂AH₈), and controlling the hydration kinetics, which subsequently

transform into more stable phases, thereby enhancing the material's long-term strength (Weise, et al., 2023).

The use of various chemical materials for soil stabilization can improve the physical and mechanical properties of low-bearing-capacity soils. Combining multiple chemical materials can further enhance stabilization potential (Zada, et al., 2023; Barman & Dash, 2022). For example, (Liangyou, et al., 2016) has been revealed that the activity of nickel-iron slag powder can be increased by adding activators, such as calcium oxide and sodium sulfate, to enhance the rate of the pozzolanic reaction. Meanwhile, (Harikaran, et al., 2023) mentioned that a combination of limestone and eggshell materials has been shown to enhance both the physical and mechanical characteristics of expansive soils.

North Maluku Province has substantial pumice reserves, particularly on Tidore Island as presented in Figure 1. Currently, pumice from Tidore is mainly used as an alternative material to replace both coarse and fine aggregates in concrete production, though its mechanical value has not been satisfactory (Gaus, et al., 2019; Nur, et al., 2022). X-Ray Diffraction (XRD) tests in several studies revealed that the chemical composition of pumice contains more than 50% SiO₂ (de Rozari, et al., 2021), (Gaus & Imran, 2018). The presence of amorphous silica in pumice presents a potential to be developed as a natural pozzolan material for soft soil stabilization. In addition to its pumice reserves in Tidore, North Maluku also contains extensive limestone reserves situated on Morotai Island. Limestone has been used for a wide range of purposes over the years as a calcium source that serves as a primary raw material in cement clinker production. Several studies have shown that the use of cement and lime can contribute to the stabilization of soft soil, helping to increase its bearing capacity by improving its physical and mechanical properties (Nugroho, et al., 2021) (Ayazhan Bazarbekova1, et al., 2021).

North Maluku, with its abundant mineral resources from the mining industry, offers significant potential for the development of materials engineering, particularly alternative materials. The use of materials, particularly from local sources, not only supports sustainable development but also reduces dependence on conventional materials, which are often environmentally unfriendly and expensive. In other words, the use of this material will support the global trend towards sustainable development and green construction solutions.

In this study, we conducted laboratory tests to analyze the effects of a combination of pumice, limestone, and aluminum hydroxide as stabilization materials on clay soil. By combining these materials, we intend to create an alternative construction material that utilizes the natural wealth of the North Maluku region. The chemical composition of limestone is rich in CaO, where (Baek, et al., 2016) His research showed that limestone contains more than 50% CaO. Meanwhile, Pumice contains more than 70% SiO₂ minerals (Rashad, 2019). Pumice and limestone, both of which are abundantly available in North Maluku, have unique chemical characteristics that, when used together with aluminum hydroxide, can improve the physical and mechanical properties of soft soil through pozzolanic reactions.

This approach presents a more sustainable method of soil stabilization and offers a practical alternative to traditional practices that typically rely on cement and other binders with a high carbon footprint. Through this

research, we hope to contribute to the development of innovative and environmentally friendly construction materials, while also supporting the local economy by utilizing region-specific resources. Furthermore, our goal is to demonstrate that local materials can play a significant role in creating high-performance, environmentally friendly construction solutions that effectively address the challenges of building on soft soils.

2. Research Material and Methodology

2.1 Research Material

In this study, we used several materials, namely: (a) clay soil taken from Subaim Village, East Halmahera Regency. The selection of this clay soil mine was based on the results of previous laboratory investigations, which showed that the clay soil in the area had low bearing capacity. This was also confirmed by the condition of the roads in the village, which experienced structural damage due to the very high resolution. (b) Pumice was taken from Tidore Island to be used as a source of silica, (c) Limestone was obtained from Morotai Island, to be used as a source of calcium, and (d) Aluminum Hydroxide [Al(OH)₃], used as a source of alumina, which was purchased commercially. A depiction of the sampling locations is shown in Figure 1.

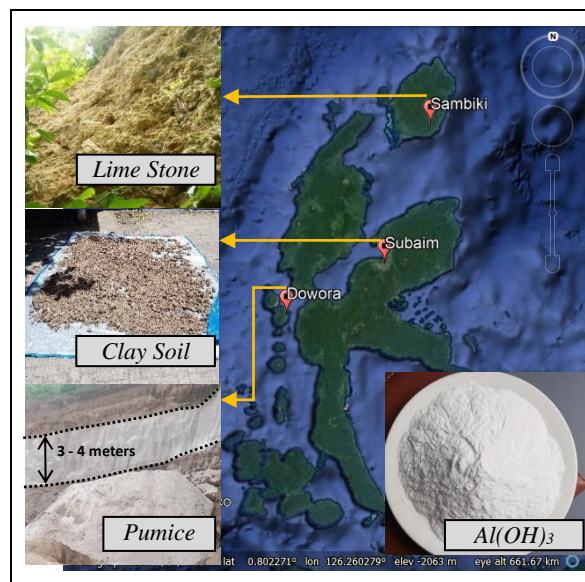


Fig 1. Materials quarry used in the research

2.2 Specimen Preparation and Testing

The procedures for testing the physical and mechanical characteristics in this research follow the standards set by the American Society for Testing Materials (ASTM). In terms of material preparation before creating the test specimens, each material was dried in the sunlight to avoid mineral changes that could result from excessive heating when using an oven. Subsequently, the pumice and limestone were milled into powder using a grinding apparatus. Only the fractions passing through a No. 400 sieve were utilized, as this level of fineness increases the particle surface area and consequently promotes faster chemical reactions on the material surfaces (Janz, 2002; Etim, et al., 2021).

The composition design of each stabilizing agent used in this study was based on the dry density (γ_{dry}) ratio of the clay soil. The pumice content used was 6%, while the aluminum hydroxide content was 4%. This refers to our

previous research, which showed that the optimal mechanical properties are achieved with a silica-to-alumina weight ratio of 1.5 (Siregar, et al., 2024). Further, the percentage of limestone content addition is set at 2%, 4%, and 6%, and the number of samples tested for each variations are 3 units.

The mixing process was carried out manually for 10–15 minutes to ensure a homogeneous mixture (Caraşca, 2016). The test specimens were then moulded using cylinders with a diameter of 35 mm and a height of 70 mm. Unconfined compressive strength testing was conducted after all specimens had been open-air-curing for 3, 7, 14, and 28 days.

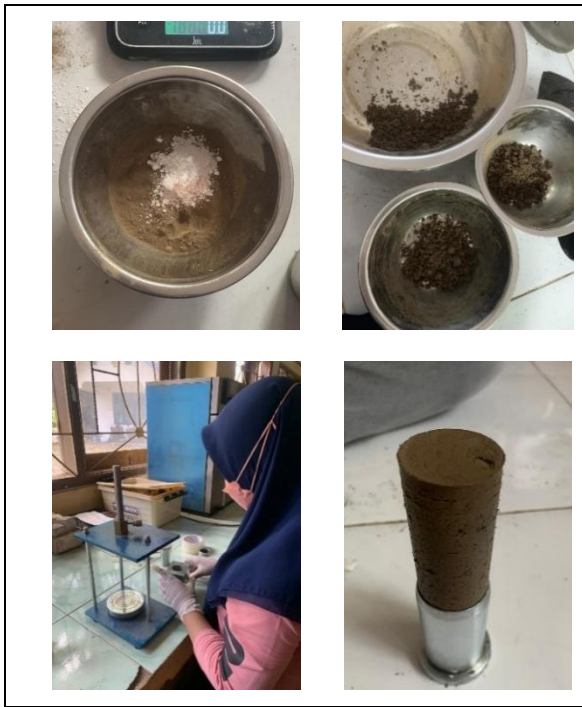


Fig 2. Steps in the Preparation of Test Samples

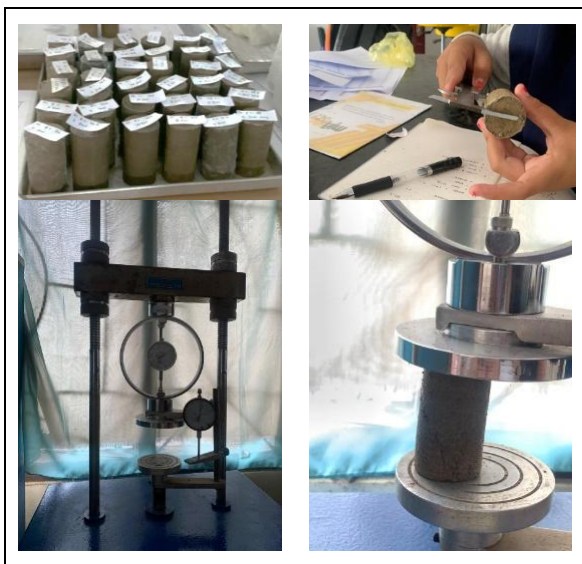


Fig 3. Process of Unconfined Compressive Strength Testing

3. Results and Discussions

3.1 Clay Soil Properties

The results of the physical characteristics test on clay soil are shown in Table 1.

Table 1. Soil Test Results

Properties	Value		
Physical	Gravity Spesific (Gs)	2,11	
	Optimum Moisture Content (wopt, %)	33,08	
	Gradation	sand (%)	8,4
		silt (%)	14,3
		clay (%)	77,3
	Atterberg Limit	Liquid Limit (LL)	64,92
		Plasticity Limit (PL)	41,34
Plasticity Index (PI)		23,58	
MDD (gr/cm ³)		1,09	
Mechanical	Compressive Strength (kg/cm ²)	0,457	

Based on the USCS classification (ASTM D2487), the results of this test show that the clay material used has peat soil characteristics, and can be classified as organic clay soil with high plasticity (OH). This is based on: specific gravity (Gs) of 2.11, clay fraction of 77.3%, liquid limit of 64.92%, and plasticity index of 23.58%. Furthermore, based on the USCS classification system and by plotting the liquid limit and plasticity index on the Casagrande chart, the soil sample is classified as a highly plastic organic soil (OH). From a mechanical standpoint, the material also demonstrates a very low bearing capacity, with an unconfined compressive strength of 0.457 kg/cm².

3.2 Unconfined Compression Strength Characteristic

The results of the unconfined compressive strength test for each variation in the addition of limestone (2%, 4%, and 6%) and curing durations of 3, 7, 14, and 28 days are presented in Table 2. Overall, all variants showed a significant increase in strength as the curing period increased. The sharpest average increase occurred during the transition from day 7 to day 14. The 4% limestone variant was the best composition. At 28 days, this variation reached the highest strength of 41.84 kg/cm². This figure is much higher than that of the 2% variation (31.31 kg/cm²) and the 6% variation (35.89 kg/cm²). A decrease in strength occurred when the limestone content was increased from 4% to 6%. Although the results at the 6% level were still better than those at the 2% level, this indicates that excessive addition of limestone actually begins to reduce the density or structural performance of the mixture.

Table 2. UCS Results

Variation Limestone	Compressive strength (kg/cm ²)			
	Curing period (days)			
	3	7	14	28
2%	4.40	9.38	21.28	31.31
4%	5.10	15.80	27.23	41.84
6%	4.78	12.81	24.33	35.89

This increase in mechanical values demonstrates the role of limestone in providing calcium ions (Ca²⁺), which function as a catalyst to accelerate the pozzolanic reaction between silica-containing minerals derived from pumice and aluminates from aluminium hydroxide (Argin & Uzal, 2022). In other words, a higher limestone content accelerates the formation of hydration products,

including C-S-H and C-A-S-H, contributing to the increased strength between particles in the matrix, both in the early and long-term stages of the material.

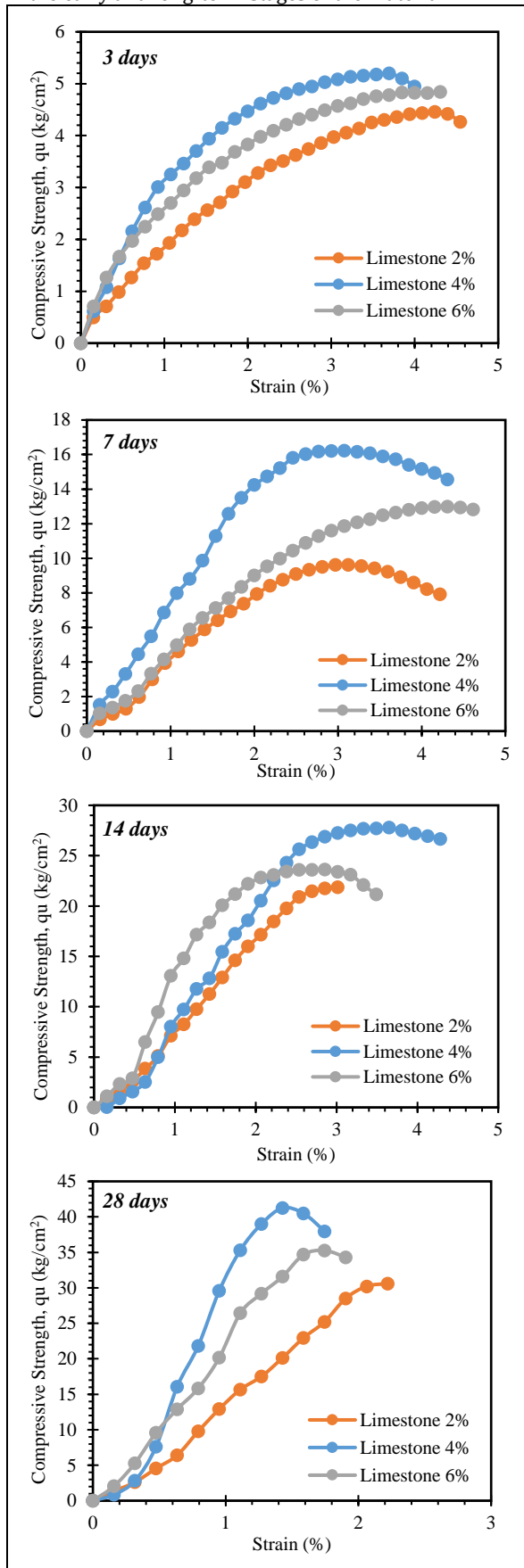


Fig 4. Stress and Strain from UCS Test.

Although limestone percentages of 2% and 6% can increase the matrix strength, there is a point where the strength increase starts to decline. This may be due to the calcium saturation process within the matrix, where a higher limestone percentage provides a large amount of calcium ions (Ca^{2+}). At a certain concentration, these ions can become saturated in their reactions with silica and aluminate (Kang, et al., 2024). Once this point is reached, the addition of limestone no longer contributes significantly to the formation of additional hydration products, as the main reactive constituents have been depleted. The same principle applies when the limestone content is below the required threshold, where an insufficient amount of limestone is present, limiting the development of these reaction products.

The results of this study, when compared with the results of previous studies that only used one stabilization material, produced better performance. For example, the unconfined compressive strength (UCS) showed a significant increase, ranging from 0.295 to 0.305 kg/cm^2 at a curing age of 3 days in peat soil stabilized with cement (Erdawaty, et al., 2025). In a separate investigation, clay soil treated with 30% pumice and cured for a week exhibited a compressive strength of 4.44 kg/cm^2 (Cimen, et al., 2015). Furthermore, soft soil stabilized with a blend of charcoal and pumice, also cured for 7 days, demonstrated a compressive strength of 3.19 kg/cm^2 (Fithria & Kusumastuti, 2022). Based on this comparison, it can be concluded that the stabilization of soft soil with multiple stabilizers can increase compressive strength value and durability in various environmental conditions.

The stress-strain curves presented in Figure 4 can be explained by the influence of limestone percentages from 2% to 6%, and curing periods consistently increase the material's stiffness. The graph shows that the curing period has a significant effect on changes in the stiffness. At 3 days, the curve tends to be flatter and longer. This indicates that the material is still highly elastic and soft because the hydration process or chemical hardening has not yet been fully completed. The strain value reaches approximately 4% before the material fails, which is significantly higher than the strain at 28 days (which is only about 1–2%).

Table 3. Modulus Elasticity Analysis Results

Curing Periode	Lime stone	Max. Strength (σ_{max})	Modulus Elasticity (E)
days	%	kg/cm^2	kg/cm^2
3	2	4.46	2.09
	4	5.2	3.51
	6	4.84	3.21
7	2	9.62	3.16
	4	16.21	7.22
	6	12.98	3.76
14	2	21.85	6.05
	4	27.79	15.45
	6	23.63	10.21
28	2	31.31	10.1
	4	41.84	25.31
	6	35.89	20.31

Based on the table 3, there is a non-linear relationship between lime content and stiffness. Adding limestone up to 4% resulted in the most significant increase in the modulus of elasticity (E) at every test age. However, at a 6% content, the stiffness value actually decreases (regresses). This indicates that 4% is the saturation

threshold at which the lime particles interact most optimally with the soil minerals. Beyond this point, the excess lime no longer functions as a binder but rather as a passive filler that actually slightly loosens the bonds between the native soil particles.

The effect of the curing period of the test specimen on the increase in unconfined compressive strength is clearly shown in Figure 5. From the observation of the results, it can be explained that the material strength continues to increase as the curing duration increases from 3 days to 28 days. This continuous increase in strength indicates that the pozzolanic reaction has improved the structural integrity of the material during the curing period. The longer the curing time, the more complete the reaction, especially the pozzolanic reaction involving silica and alumina with calcium ions provided by limestone. This mechanism leads to the development of primary hydration products, including Calcium Silicate Hydrate (C-S-H) and Calcium Aluminate Hydrate (C-A-H), which contribute significantly to the material's compressive strength. These results also show that the optimum limestone addition rate of 4% supplying compressive strength, with a 114-fold increase compared to the untreated soil. Therefore, it can be concluded that adding lime as a stabilizing material can significantly improve the mechanical properties of soft soil, especially when combined with other reactive materials such as pumice, microsilica, and aluminum hydroxide.

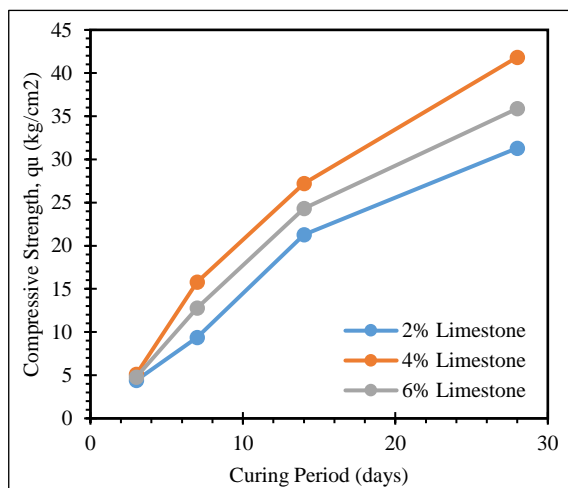


Fig 5. Comparison of Unconfined Compressive Strength Values during the Curing Period

The findings of this study indicate that increasing the percentage of limestone in the mixture resulted in a substantial increase in material strength across all tested drying periods. This indicates that limestone not only functions as an inert filler but also plays an active role in the hydration reactions occurring within the matrix. These reactions help form stronger bonds between soil particles and hydration products, thus strengthening the material's internal structure. The presence of limestone facilitates a continuous supply of calcium ions (Ca^{2+}), which act as catalysts in pozzolanic reactions, accelerating the formation of hydrated compounds that contribute to the material's long-term strength and stability.

4. Conclusions

Based on the results of the unconfined compressive strength test in this study, several important points that

can be concluded, comprise: limestone has an important role in soft soil stabilization engineering, where limestone not only functions as a filler but also functions as a catalyst that can accelerate pozzolanic reactions, both Calcium Silicate Hydrate (CSH), Calcium Aluminate Hydrate (CAH), and Calcium Silica Aluminate Hydrate (CSAH). The right combination of several stabilization materials can contribute to increasing the mechanical value of soft soil better when compared to using a mono stabilization material. However, this must be based on the mineral characteristics of the soil and the stabilization materials used.

In addition, further research is needed regarding environmental influences, especially changes in water content.

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References

- Abdulkareem, M., Havukainen, J. & Horttanainen, M., 2019. How environmentally sustainable are fibre reinforced alkali-activated concretes?. *Journal of Cleaner Production*, p. <https://doi.org/10.1016/j.jclepro.2019.07.076>.
- Argin, G. & Uzal, B., 2022. Enhancement of pozzolanic activity of calcined clays by limestone powder addition. *Construction and Building Materials*, p. <https://doi.org/10.1016/j.conbuildmat.2021.122789>.
- Ayazhan Bazarbekova1, C.-S. S. K. A., Kim, J. R., Zhang, D. & Moon, S.-W., 2021. Potential of limestone powder to improve the stabilization of sulfate-contained saline soil. *IOP Conference Series: Materials Science and Engineering*, Issue DOI 10.1088/1757-899X/1040/1/012016.
- Baek, C.-S., Seo, J., Jin-Sang, C. & Kye-Hong, C., 2016. Effects of Physicochemical/Mineralogical Characteristics of Limestones and Porosity after Calcination on Desulfurization Reactivities. *Journal of the Korean Ceramic Society*, pp. 34-42, DOI:10.4191/kcers.2016.53.1.34.
- Barman, D. & Dash, S. K., 2022. Stabilization of expansive soils using chemical additives: A review. *Journal of Rock Mechanics and Geotechnical Engineering*, Issue <https://doi.org/10.1016/j.jrmge.2022.02.011>, pp. 1319 - 1342.
- Bayiha, B. N. et al., 2023. Comparative study of the effects of a natural pozzolan and an artificial pozzolan on the hydraulic properties of Portland cement mortar. *Global Journal of Engineering and Technology Advances*, 14(1, <https://doi.org/10.30574/gjeta.2023.14.1.0021>), p. 107-119.
- Caraşca, O., 2016. Soil improvement by mixing: techniques and performances. *Energy Procedia*, pp. 85-92.
- Çimen, Ö., Saltan, M. & Keskin, S. N., 2015. Stabilization of clayey subgrade with waste pumice for road infrastructure. *Science Engineering Composite Material*, 22 (5, DOI : 10.1515/secm-2013-0315), p. 583-590.

- Das, B. M., 2019. *Advanced Soil Mechanics*, Fifth Edition. London: CRC Press.
- de Rozari, P. et al., 2021. The use of pumice amended with sand media for domestic wastewater treatment in vertical flow constructed wetlands planted with lemongrass (*Cymbopogon citratus*). *Heliyon*, 7(7), <https://doi.org/10.1016/j.heliyon.2021.e07423>, pp. 1-12.
- Dodson, V., 1990. *Pozzolans and the Pozzolanic Reaction in Concrete Admixture*. Boston, MA: Springer.
- Erdawaty, et al., 2025. A Study On Soil Bearing Capacity Strengthening Using Soil Cement On Jagebob Road With Unconfined Compression Test. *Journal of Geoscience, Engineering, Environment, and Technology*, 10(4), DOI: 10.25299/jgeet.2025.10.4.24848, pp. 493-593.
- Etim, R. K., Ekpo, D. U., Attah, I. C. & Onyelowe, K. C., 2021. Effect of micro sized quarry dust particle on the compaction and strength properties of cement stabilized lateritic soil. *Cleaner Materials*, Issue <https://doi.org/10.1016/j.clema.2021.100023>, pp. 1-17.
- Fithria, R. & Kusumastuti, D. P., 2022. The Effect of Wood Charcoal Powder and Pumice Powder on The Parameters of Shear Strength of Clay Soil. *Indonesian Geotechnical Journal*, 1(2), <https://doi.org/10.56144/igi.v1i2.14>, pp. 50-58.
- Gaus, A. & Imran, 2018. *Towards Eco Green Construction With Pumice Fine Aggregate Concrete*. s.l., Atlantis Press.
- Gaus, A., Imran, Anwar, C. & Novianti, L., 2019. Experimental Study on the Use of Pumice on the Rigid Pavement. *EPI International Journal of Engineering*, pp. 61-67.
- Gómez, S. d. R. & F. Rojas, M., 2013. *Natural pozzolans in eco-efficient concrete in Eco-efficient concrete*. Cambridge: Woodhead Publishing.
- Harikaran, M., Kulanthaivel, P., Gokulakannan, S. & Vinodhkumar, S., 2023. Eco-friendly soil stabilization: a combined approach using lime and waste eggshell powder. *Global Nest*, 7(<https://doi.org/10.30955/gnj.005077>), p. 25.
- Janz, M. & J. S., 2002. *The Function of Different Binding Agents in Deep Stabilization*. s.l.:Swedish Deep Stabilization Research Centre.
- Kang, I., Shin, S. & Kim, J., 2024. Optimal Limestone Content on Hydration Properties of Ordinary Portland Cement with 5% Ground Granulated Blast-Furnace Slag. *Material*, p. <https://doi.org/10.3390/ma17133255>.
- Kimpraswil, 2002. *Panduan Geoteknik 4: Pengujian tanah lunak (Pt T 09-2002-B)*. Jakarta: Kimpraswil.
- Liangyou, L. et al., 2016. Influence of nickel-iron slag used as admixture on cement properties. *Bulletin of the Chinese ceramic society*.
- Mahasenan, N., Smith, S. & Humphreys, K., 2003. *The Cement Industry and Global Climate Change Current and Potential Future Cement Industry CO2 Emissions*. Kyoto. Japan, s.n., pp. 995-1000, DOI:10.1016/B978-008044276-1/50157-4.
- McCarthy, M. J. & Dyer, T. D., 2019. *Pozzolanas and Pozzolanic Materials*. *Lea's Chemistry of Cement and Concrete*, Issue DOI: 10.1016/C2013-0-19325-7, pp. 363-467.
- Menéndez, E. et al., 2020. Sustainable and Durable Performance of Pozzolanic Additions to Prevent Alkali-Silica Reaction (ASR) Promoted by Aggregates with Different REaction Rates. *Applied Science*, doi:10.3390/app10249042, pp. 1-24.
- Nugroho, S. A., Wibisono, G., Ongko, A. & Mauliza, A. Z., 2021. The Influence of High Plasticity and Expansive Clay Stabilization with Limestone on Unconfined Compression Strength. *Journal of The Civil Engineering Forum*, 7(2), <https://doi.org/10.22146/jcef.59438>, pp. 147-154.
- Nur, M. M., Kusnadi & Rauf, I., 2022. Compressive Strength Characteristics of Lightweight Concrete with Modified EPS and Pumice Sand. *IJEBD*, pp. 830-835.
- Rashad, A. M., 2019. A short manual on natural pumice as a lightweight aggregate. *Journal of Building Engineering*, p. <https://doi.org/10.1016/j.jobe.2019.100802>.
- Raveendran, N. & Vasughi, K., 2024. Synergistic effect of nano silica and metakaolin on mechanical and microstructural properties of concrete: An approach of response surface methodology. *Case Studies in Construction Materials*, 20(<https://doi.org/10.1016/j.cscm.2024.e03196>).
- Siregar, F., Saputra, M. R., Gaus, A. & Rauf, I., 2024. Performance of Nickel Slag as a Stabilization Material for Soft Soil. *South Asian Res J Eng Tech*, 6(1), pp. 29-34.
- Weise, K., Ukrainczyk, N. & Koenders, E., 2023, . Pozzolanic Reactions of Metakaolin with Calcium Hydroxide: Review on Hydrate Phase Formations and Effect of Alkali Hydroxides, Carbonates and Sulfates. *Materials & Design*, 231(<https://doi.org/10.1016/j.matdes.2023.112062>).
- Zada, U. et al., 2023. Recent advances in expansive soil stabilization using admixtures : current challenges and opportunities. *Case Studies in Construction Materials*, 18(<https://doi.org/10.1016/j.cscm.2023.e01985>), pp. 1-16.



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