International Journal of Innovative Research in Engineering and Management (IJIREM)
ISSN(Online): 2350-0557, Volume-12, Issue-1, February 2025
https://doi.org/10.55524/ijirem.2025.12.1.1
Article ID IJIR3059, Pages 1-6
www.ijirem.org

Eco-Friendly Innovation in Soft Soil Stabilization: Combining Fine Pumice, Aluminium Hydroxide, and Lime to Enhance Road Bearing Capacity

Budiman A. Majid[1], Abdul Gaus[2]*, Yusrin Hasim[3], Ichsan Rauf[4], and Komang Arya Utama[5]

[1, 2, 3, 4] Department of Civil Engineering, Khairun University, Ternate, Indonesia
[5] Department of Civil Engineering, State University of Gorontalo, Gorontalo, Indonesia

Received: 10 December 2024 Revised: 23 December 2024 Accepted: 09 January 2025

ABSTRACT- Soft soil is a material with low bearing capacity that often poses a major challenge in road construction, particularly in areas with high water content. This study aims to enhance the bearing capacity of soft soil through chemical stabilization using a combination of pumice, aluminium hydroxide (AH), and lime, with lime content variations of 2%, 4%, and 6%. The soft soil samples were collected from Subaim Village, East Halmahera, which naturally has a CBR value of 4,49% (categorized as "Poor to Fair") and is only suitable for use as a subgrade layer. Testing was conducted in accordance with ASTM standards on specimens soaked for 3 to 28 days to assess the impact of lime content and curing duration on the CBR value. The results showed that the addition of lime significantly improved the CBR value compared to the natural soil. At 2% lime content, the CBR value increased from 9,90% to 26,09%, while 4% lime produced the highest CBR value of 33,28%, representing an improvement of over sevenfold compared to the natural soil. Lime at 6% resulted in a CBR value of 27,89%, but it was less efficient compared to 4% lime. Based on CBR value classification, stabilization with 4% lime is categorized as "Good" and can be used as a base or sub-base layer for road construction under medium to heavy traffic loads. This research demonstrates that the combination of pumice, $Al(OH)_3$, and lime is an effective, environmentally friendly, and economical local material alternative for improving the bearing capacity of soft soil. It also offers a sustainable solution for road infrastructure development in remote areas.

KEYWORDS- Soft Soil, Stabilization, Pumice, Aluminium Hydroxide, Limestone, Soil Bearing Capacity.

I. INTRODUCTION

Soft soil is one of the types of soil that often poses significant challenges in the field of construction, particularly in swampy areas, lowlands, or regions with high water content. Soft soil exhibits poor mechanical characteristics, such as low bearing capacity, high compressibility, and significant deformation under load [1]. These conditions create major obstacles in infrastructure construction, especially in road foundation projects, as they can lead to excessive deformation, cracks in road layers, and even structural failure. Therefore, improving soft soil, particularly through stabilization methods, is a crucial step to enhance soil stability and ensure the longevity and safety of infrastructure.

In road construction projects, the subgrade layer serves as the primary support layer that plays a critical role in bearing dynamic loads from traffic. Unstable subgrade soil can cause settlement or damage to the pavement layers. The main parameter used to evaluate the subgrade soil's ability to support vehicle loads is the California Bearing Ratio (CBR). A low CBR value, commonly found in soft soil, indicates poor load-bearing capability, necessitating improvement before infrastructure development can proceed. Therefore, increasing the CBR value of soft soil is a primary objective of soil stabilization.

Chemical stabilization methods are among the most widely used techniques, involving the addition of specific chemical materials such as cement, NaCl, lime, or other additives. These methods aim to improve the mechanical properties of the soil in accordance with technical specifications. Cement is a conventional material commonly used due to its proven ability to significantly enhance soil strength through the formation of binding compounds such as calcium silicate hydrate (C-S-H) [2]. However, the use of cement has certain disadvantages, particularly in terms of environmental impact. Cement production generates high carbon emissions, contributing to global warming [3]. Additionally, cement tends to be expensive and less accessible in some remote areas, making its use not always economically viable. Therefore, alternative stabilization materials that are more environmentally friendly and cost-effective are required.

North Maluku possesses significant deposits of limestone, particularly in Morotai Island. Limestone has long been used as an alternative stabilization material that is more environmentally friendly than cement. Limestone serves as a calcium source, reacting with soil minerals—particularly clay—through ion exchange processes and the formation of compounds like calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H) [4]. Lime enhances soil texture and reduces its plasticity, improving rigidity and bearing capacity [5]. However, the effectiveness of lime stabilization is highly dependent on soil type and characteristics, often requiring a long time to achieve optimal results. In many cases, lime alone is insufficient to achieve significant strength improvement [6], necessitating its combination with other materials.

In addition to limestone, North Maluku is rich in pumice deposits, particularly on Tidore Island. This natural material possesses pozzolanic properties due to its high silica content. X-ray diffraction (XRD) studies show that the chemical composition of pumice contains more than 50% SiO_2[7][8], indicating its potential to react with lime and water to form binding compounds that enhance soil strength. However, pozzolanic reactions require specific conditions, such as sufficient lime availability and an alkaline environment, to yield optimal results. Consequently, using pumice as a standalone stabilization material is often inefficient and requires additional materials to improve its effectiveness.

The combination of multiple pozzolanic materials offers a more effective approach to soil stabilization[9][10]. Aluminium hydroxide acts as a catalyst, accelerating the chemical reactions between pumice, lime, and soil minerals. It facilitates the formation of binding compounds such as calcium aluminate hydrate (C-A-H), significantly contributing to soil strength improvement [11]. Additionally, aluminium hydroxide creates a more reactive chemical environment, speeding up stabilization processes that typically require a long time.

This approach leverages the benefits of each stabilization material, resulting in significant mechanical improvements[12][13]. Pumice provides active pozzolanic material that strengthens soil through the formation of silica and alumina bonds. Aluminium hydroxide accelerates chemical reactions and the formation of binding compounds, while lime creates a reactive environment supporting stabilization processes. This combination not only significantly increases the CBR value of the soil but also accelerates the stabilization process, making it more efficient compared to using single materials.

Beyond its technical advantages, this approach also offers environmental and economic benefits. The use of pumice and lime, both locally available materials, is more environmentally friendly than cement. The production processes for pumice and lime generate substantially lower carbon emissions, contributing to reduced environmental impact. Additionally, utilizing local materials reduces transportation and logistics costs, making this solution more cost-effective, especially in remote or hard-to-access areas.

II. RESEARCH METHODS

A. Materials

The materials used in this study include: (a) Clay soil obtained from Subaim Village in East Halmahera Regency. This is based on laboratory investigations showing that the roads in this village are built on clay layers, resulting in structural road damage throughout the village. (b) Pumice sourced from Tidore Island, serving as a silica source. (c) Limestone sourced from Morotai Island, serving as a calcium source. (d) Aluminium hydroxide [$Al(OH)_3$], serving as an aluminate source, procured from the market. The sampling locations for these materials are illustrated in Figure 1.

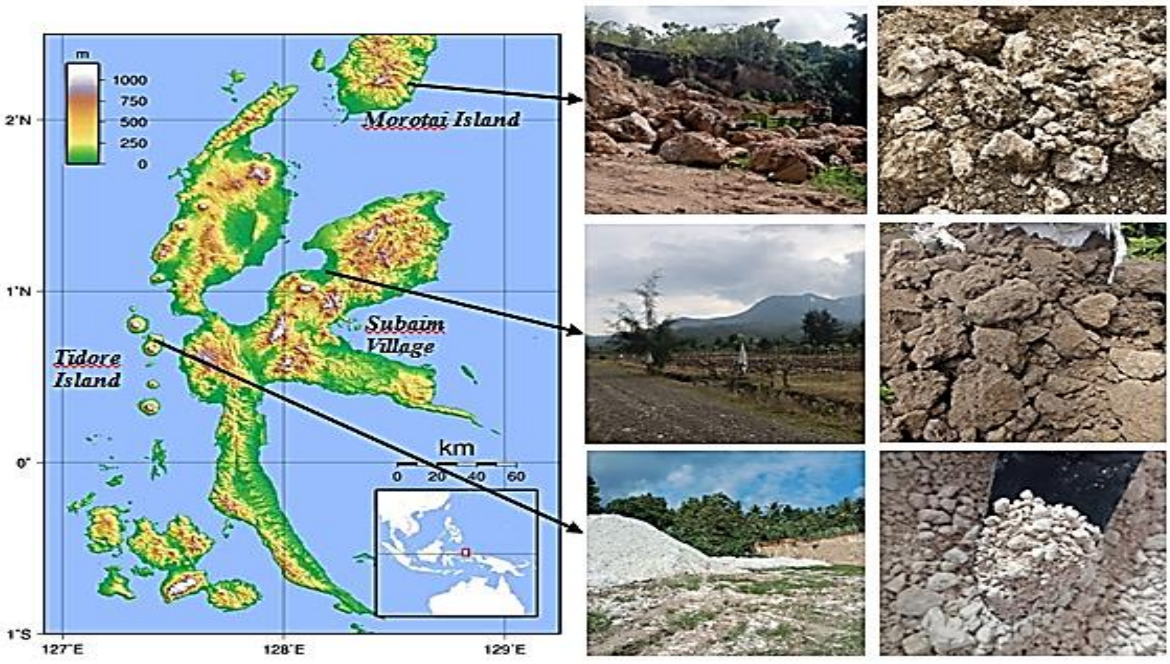

Figure 1: Source of Research Material

B. Preparation and Testing of Specimen

The testing procedure for the physical and mechanical characteristics in this study adhered to the standards of the American Standard Testing Materials (ASTM). During the material preparation stages prior to specimen fabrication, all materials were dried under sunlight to prevent mineral alterations caused by excessive heating in an oven. Subsequently, pumice and limestone were ground using a grinding machine. The pumice and limestone used in this study were sieved through a No. 400 sieve, aiming to increase the surface area of the particles to enhance the rate of chemical reactions occurring on the material surfaces [14][15]. See the below figure 2.

Figure 2: Stages of Sample Preparation

The mixture composition of clay soil, pumice, limestone, and aluminium hydroxide was based on the dry weight of the clay soil. The percentage of pumice used was 6%, while aluminium hydroxide was set at 4%. This was based on our previous research, which demonstrated that the optimal mechanical properties were achieved with a silica-to-aluminate weight ratio of 1,5 [16]. The variations in lime addition were 2%, 4%, and 6%. See the below figure 3.

Figure 3: CBR Testing Process

The mixing process was performed manually for 10–15 minutes to ensure the mixture was homogeneous [17][19]-[25]. The test specimens were cylindrical, the set consists of a 6 x 7-inch (152 x 178 mm) mold body and a 2 inch (51 mm) compaction Collar, and a perforated mold base with threaded rods and wing nuts. California Bearing Ratio (CBR) testing was conducted after the specimens were cured in open air for 3, 7, 14, 21, and 28 days.

III. RESULTS AND DISCUSSIONS

A. Characteristics of Untreated Soil

The results of the physical parameter testing on the clay soil used in this study are presented in Table 1, where the following values were obtained: specific gravity (Gs) of 2,11; clay dominance of 77,3%; liquid limit of 64,92%; and plasticity index of 23,58%. Based on these values, according to the USCS classification by plotting the IP and LL values on the Casagrande chart, the soil can be classified as organic soil with a high organic content (OH). Furthermore, the CBR test results also indicate that the clay soil has very low bearing capacity, with a value of 4,49%. Based on this CBR value, the clay soil is categorized as having "poor to fair" bearing capacity [18][26]-[34]. This indicates that natural soil has limited bearing capacity. Therefore, this natural soil can only be utilized as a sub-grade layer in road construction, particularly for roads with light traffic intensity.

Table 1: Soft Soil Properties

Soft soil properties		Value
Physical characteristics	Specific Gravity (Gs)	2,11
	Water Content (W_{opt}, %)	33,08
	Sieve Analysis	
	Sand (%)	8,4
	Silt (%)	14,3
	Clay (%)	77,3
	Atterberg Limit	
	Liquid Limit (LL)	64,92
	Plastic Limit (PL)	41,34
	Plasticity Index (PI)	23,58
Mechanical characteristics	Density (kN/m^3)	10,9
	CBR (%)	4,49%

B. The Result of the CBR Measurement

The results of the CBR tests on clay soil stabilized with pumice, aluminium hydroxide, and varying lime additions of 2%, 4%, and 6% are shown in Figure 4. The graph indicates that the addition of lime and the curing duration significantly improved the soil's bearing capacity. Soil with 2% lime addition exhibited an increase in bearing capacity compared to natural soil. After 3 days of curing, the load values reached 296,86 lbs at a penetration of 0,1 inches and 404,81 lbs at 0,2 inches, with gradual increases over the curing period. After 28 days, the load values rose to 782,62 lbs at 0.1 inches and 944,55 lbs at 0.2 inches of penetration.

The addition of 4% lime demonstrated a significant improvement in bearing capacity, especially after curing for 7 to 28 days. At 28 days, the load values reached 998,52 lbs at a penetration of 0,1 inches and 1376,34 lbs

at 0,2 inches. These results indicate that 4% lime begins to provide optimal stabilization effects, forming stronger bonds between soil particles through pozzolanic reactions. On the other hand, at a lime concentration of 6%, the recorded loads were 836,60 lbs and 1133,45 lbs at penetrations of 0,1 inches and 0,2 inches, respectively, after 28 days of curing.
Overall, the CBR test results show that both 4% and 6% lime additions yielded excellent outcomes, with the 6% lime addition being the most effective in enhancing the soil's bearing capacity. Curing for 28 days produced optimal results, highlighting the importance of curing time in maximizing the effectiveness of soil stabilization. In other words, the addition of 2% lime is only suitable for light to moderate load applications, while 4% and 6% lime are effective for heavy load applications.

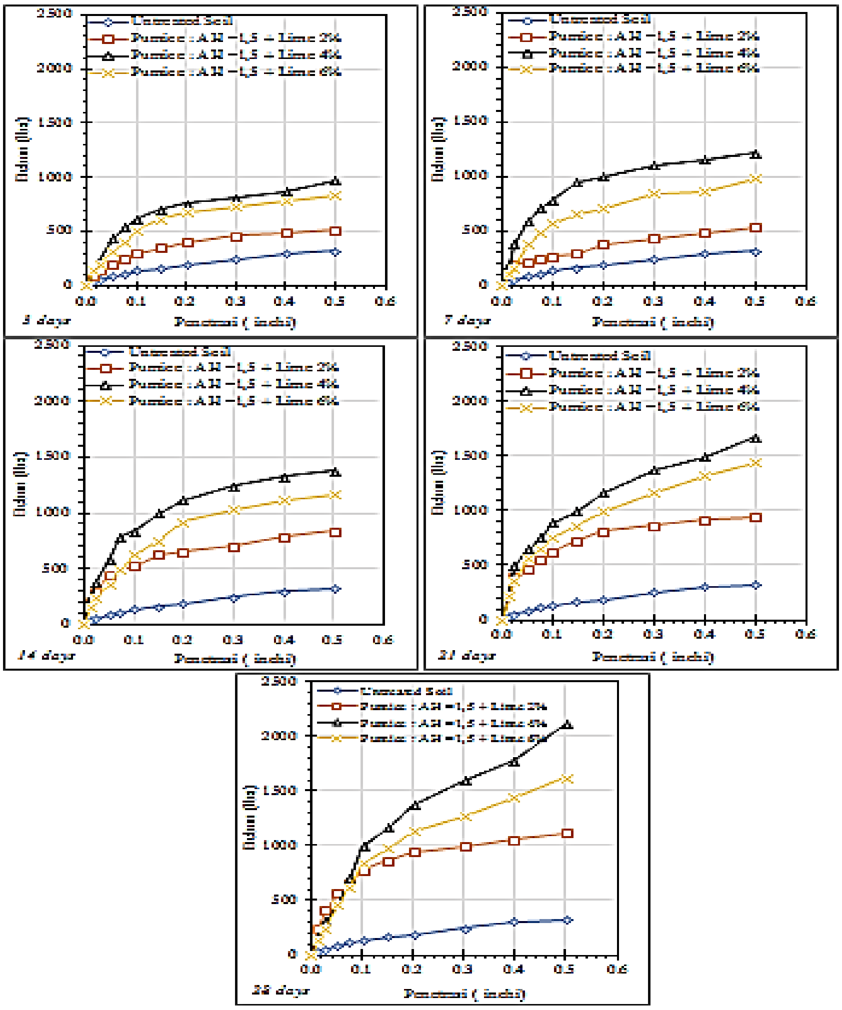

Figure 4: The Result of the CBR Measurement

C. CBR Values and Their Application in Road Construction

Figure 5 illustrates the relationship between curing time and the California Bearing Ratio (CBR) values for natural soil and soil stabilized using a mixture of pumice, lime, and lime at varying concentrations of 2%, 4%, and 6%. The application of this soil stabilization method shows a significant increase in CBR values compared to natural soil. For 2% lime stabilization, the CBR value increased from 9.90% to 26.09% after 28 days of curing, while stabilization with 4% lime resulted in a more significant increase, from 20.69% to 33.28%. Meanwhile, 6% lime stabilization showed an improvement from 17.09% to 27.89% over the same period. These results indicate that the highest CBR value was achieved with 4% lime stabilization, which demonstrated an increase of more than sevenfold compared to natural soil.

Based on the CBR value classification, soil stabilization using 4% lime falls into the "Good" category, indicating that the stabilized soil can be utilized as a Base or Sub-base layer in road construction. This combination provides the highest CBR value compared to 2% and 6% lime and shows consistent results throughout the curing period. With a final CBR value of 33.28% on the 28th day, this soil demonstrates sufficient bearing capacity for use in road construction subjected to moderate to heavy traffic loads, such as primary highways or arterial roads.
The results of this study indicate that the stabilization method using a mixture of pumice, aluminium hydroxide, and 4% lime is an effective solution for improving the mechanical characteristics of soil, particularly its CBR value. With a significant increase in bearing capacity, this technique enables the use of previously unsuitable local soils as construction materials. The application of this method has the potential to enhance technical efficiency

and sustainability in road infrastructure development, especially in areas requiring a high-bearing-capacity subbase layer.

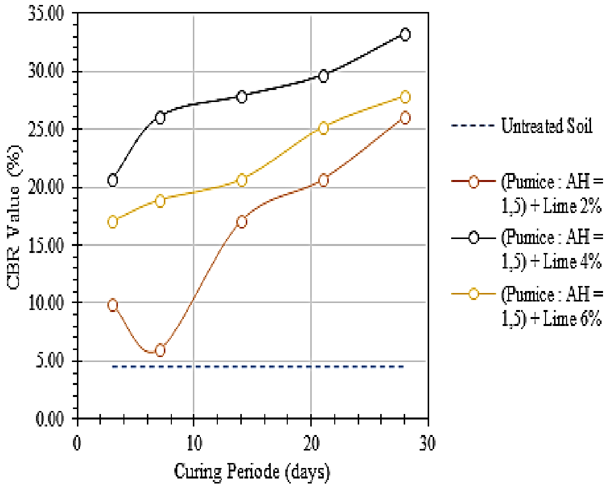

Figure 5: The Effect of Time and Curing Period on CBR Values

IV. CONCLUSION

This study concludes that soft soil stabilization using a combination of pumice, aluminium hydroxide (AH), and lime significantly improves the soil's California Bearing Ratio (CBR) compared to its natural condition. Natural soil, with a CBR value of 4.49%, categorized as "Poor to Fair," is only suitable for use as a sub-grade layer. The addition of lime at concentrations of 2%, 4%, and 6% demonstrated progressive improvements in CBR values, with 4% lime yielding the highest value of 33.28%, classified as "Good." This makes it suitable for use as a Base or Sub-base layer for roads subjected to medium to heavy traffic loads. The findings affirm that 4% lime is the most efficient concentration for improving soil bearing capacity in terms of both effectiveness and result stability. Additionally, the study highlights the importance of curing time in maximizing the stabilization effects, as CBR values continued to increase up to 28 days of curing. The use of local materials, such as pumice and lime, not only provides a superior technical solution but also offers a more environmentally friendly and cost-effective alternative to conventional cement stabilization. Therefore, this method has the potential to become a sustainable solution for improving subgrade quality in remote areas with limited access to conventional construction materials.

CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

REFERENCES

[1] M. Das, Principles of Geotechnical Engineering 7th Edition, Stamford, USA: Cengage Learning, 2010. Available from: https://dl.icdst.org/pdfs/files/f26ec24b602af7971800c8c327a3b3bd.pdf

[2] Y. Zhou, M. Huo, L. Zhang and Q. Guan, "Strength Development and Solidification Mechanism of Soils with different properties stabilized by Cement-Slag-based Materials," Case Studies in Construction Materials, no. 2024. Available from: https://doi.org/10.1016/j.cscm.2024.e04034

[3] Z. Cao, E. Masanet, A. Tiwari and S. Akolawala, "How does concrete and cement industry transformation contribute to mitigating climate change challenges?," Resources, Conservation & Recycling Advances, no. 2022. Available from: https://doi.org/10.1016/j.rcradv.2022.200084

[4] L. Sharma, N. Sirdesai, K. Sharma and T. Singh, "Experimental Study to Examine the independent Roles of Lime and Cement on the Stabilization of a Mountain Soil: A Comparative Study," Applied Clay Science, no. 2018. Available from: https://doi.org/10.1016/j.clay.2017.11.012

[5] S. A. Nugroho, G. Wibisono and A. Z. Mauliza, "High Plasticity Influence and Expansive Clay Stabilization with Limestone on Unconfined Compression Strength Tests," Journal of the Civil Engineering Forum, no. 2021. Available from: https://doi.org/10.22146/jcef.59438

[6] S. Malkanthi, N. Balthazaar and A. Perera, "Lime Stabilization for Compressed Stabilized Earth Blocks with reduced Clay and Silt," Case Studies in Construction Materials, no. 2020. Available from: https://doi.org/10.1016/j.cscm.2019.e00326

[7] P. de Rozari, D. S. Krisnayanti, Refli, K. V. Yordanis and M. R. R. Atie, "The use of pumice amended with sand media for domestic wastewater treatment in vertical flow constructed wetlands planted with lemongrass (Cymbopogon citratus)," Heliyon, vol. 7, no. 7, pp. 1-12, 2021. Available from: 9https://doi.org/10.1016/j.heliyon.2021.e07423

[8] A. Gaus and Imran, "Towards Eco Green Construction With Pumice Fine Aggregate Concrete," in International Conference on Science and Technology (ICST), 2018. Available from: http://dx.doi.org/10.2991/icst-18.2018.85

[9] L. H. Ali and Y. K. Atemimi, "Effective Use of Pozzolanic Materials for Stabilizing Expansive Soils: A Review," IOP Conf. Series: Earth and Environmental Science, no. 2024. Available from: http://dx.doi.org/10.1088/1755-1315/1374/1/012014

[10] N. Abbasi and M. Mahdieh, "Improvement of Geotechnical Properties of Silty Sand soils using Natural Pozzolan and Lime," International Journal of Geo-Engineering, no. 2018. Available from: https://doi.org/10.1186/s40703-018-0072-4

[11] I. Rauf, M. T. Y. Saputra, H. Heryanto and M. F. Marsaoly, "Laboratory Investigation of the Influence of Aluminum Hydroxide on the Compressive Strength of Nickel Slag-stabilized soft soils," AIMS Materials Science, no. 2024. Available from: https://dx.doi.org/10.3934/matersci.2024060, pp. 1220-1231

[12] R. Al-Khafaji, A. Dulaimi, H. Jafer, N. S. Mashaan, S. Qaidi, Z. S. Obaid and Z. Jwaida, "Stabilization of Soft Soil by a Sustainable Binder Comprises Ground Granulated Blast Slag (GGBS) and Cement Kiln Dust (CKD)," Recycling, no. 2023. Available from: http://dx.doi.org/10.3390/recycling8010010

[13] C. S. Parmance, H. A. Coda, I. Rauf, A. Gaus and A. U. Komang, "The Effect Of Quicklime on the CBR Value of Soft Soil Stabilized with Nickel Slag and Alumunium Hydroxide," American Journal Of Applied Science And Technology, no. 2024. Available from: http://dx.doi.org/10.37547/ajast/Volume04Issue12-02

[14] M. &. J. S. Janz, The Function of Different Binding Agents in Deep Stabilization, Swedish Deep Stabilization Research Centre, 2002. Available from: https://www.sgi.se/globalassets/publikationer/svensk-djupstabilisering/sd-r9e.pdf

[15] "Effect of micro sized quarry dust particle on the compaction and strength properties of cement stabilized lateritic soil," Cleaner Materials, no. , pp. 1-17, 2021. Available from: https://doi.org/10.1016/j.clema.2021.100023

[16] F. Siregar, M. R. Saputra, A. Gaus and I. Rauf, "Performance of Nickel Slag as a Stabilization Material for Soft Soil," South Asian Res J Eng Tech, vol. 6, no. 1, pp. 29-34, 2024. Available from: http://dx.doi.org/10.36346/sarjet.2024.v06i01.004

[17] O. Carașca, "Soil improvement by mixing: techniques and performances," Energy Procedia , pp. 85-92, 2016. Available from: https://doi.org/10.1016/j.egypro.2015.12.277

[18] B. M. Das, Principles of Geotechnical Engineering 7th Edition, Stamford, USA: Cengage Learning, 2010. Available from: https://dl.icdst.org/pdfs/files/f26ec24b602af7971800c8c327a3b3bd.pdf

[19] Y. Zhou, M. Huo, L. Zhang, and Q. Guan, "Strength Development and Solidification Mechanism of Soils with Different Properties Stabilized by Cement-Slag-Based Materials," Case Studies in Construction Materials, vol. 21, 2024, Art. no. e04034. Available from: https://doi.org/10.1016/j.cscm.2024.e04034

[20] Z. Cao, E. Masanet, A. Tiwari, and S. Akolawala, "How Does Concrete and Cement Industry Transformation Contribute to Mitigating Climate Change Challenges?," Resources, Conservation & Recycling Advances, vol. 14, 2022, Art. no. 200084. Available from: http://dx.doi.org/10.1016/j.rcradv.2022.200084

[21] L.K. Sharma, N.N. Sirdesai, K.M. Sharma, and T.N. Singh, "Experimental Study to Examine the Independent Roles of Lime and Cement on the Stabilization of a Mountain Soil: A Comparative Study," Applied Clay Science, vol. 152, 2018, pp. 183-195. Available from: https://doi.org/10.1016/j.clay.2017.11.012

[22] S. A. Nugroho, G. Wibisono, and A. Z. Mauliza, "High Plasticity Influence and Expansive Clay Stabilization with Limestone on Unconfined Compression Strength Tests," Journal of the Civil Engineering Forum, vol. 7, no. 2, pp. 151-160, 2021, Available from: https://dx.doi.org/10.22146/jcef.59438

[23] S. Malkanthi, N. Balthazaar, and A. Perera, "Lime Stabilization for Compressed Stabilized Earth Blocks with reduced Clay and Silt," Case Studies in Construction Materials, vol. 13, 2020, Art. no. e00326, Available from: https://doi.org/10.1016/j.cscm.2019.e00326

[24] P. de Rozari, D. S. Krisnayanti, Refli, K. V. Yordanis, and M. R. R. Atie, "The use of pumice amended with sand media for domestic wastewater treatment in vertical flow constructed wetlands planted with lemongrass (Cymbopogon citratus)," Heliyon, vol. 7, no. 7, pp. e07423, 2021, Available from: https://doi.org/10.1016/j.heliyon.2021.e07423

[25] A. Gaus and Imran, "Towards Eco Green Construction With Pumice Fine Aggregate Concrete," in International Conference on Science and Technology (ICST), Yogyakarta, Indonesia, 2018. Available from: http://dx.doi.org/10.2991/icst-18.2018.85

[26] L. H. Ali and Y. K. Atemimi, "Effective Use of Pozzolanic Materials for Stabilizing Expansive Soils: A Review," IOP Conf. Series: Earth and Environmental Science, vol. 1374, Art. no. 012014, 2024. Available from: http://dx.doi.org/10.1088/1755-1315/1374/1/012014

[27] N. Abbasi and M. Mahdieh, "Improvement of Geotechnical Properties of Silty Sand Soils using Natural Pozzolan and Lime," International Journal of Geo-Engineering, vol. 9, Art. no. 21, 2018, Available from: http://dx.doi.org/10.1186/s40703-018-0072-4

[28] I. Rauf, M. T. Y. Saputra, H. Heryanto, and M. F. Marsaoly, "Laboratory Investigation of the Influence of Aluminum Hydroxide on the Compressive Strength of Nickel Slag-stabilized Soft Soils," AIMS Materials Science, vol. 11, no. 3, pp. 1220-1231, 2024, Available from: https://doi.org/10.3934/matersci.2024060

[29] R. Al-Khafaji, A. Dulaimi, H. Jafer, N. S. Mashaan, S. Qaidi, Z. S. Obaid, and Z. Jwaida, "Stabilization of Soft Soil by a Sustainable Binder Comprises Ground Granulated Blast Slag (GGBS) and Cement Kiln Dust (CKD)," Recycling, vol. 8, no. 1, Art. no. 10, 2023, Available from: http://dx.doi.org/10.3390/recycling8010010

[30] C. S. Parmance, H. A. Coda, I. Rauf, A. Gaus, and A. U. Komang, "The Effect Of Quicklime on the CBR Value of Soft Soil Stabilized with Nickel Slag and Aluminum Hydroxide," American Journal of Applied Science and Technology, vol. 4, no. 12, pp. 15-25, 2024, Available from: http://dx.doi.org/10.37547/ajast/Volume04Issue12-02

[31] M. & J. S. Janz, The Function of Different Binding Agents in Deep Stabilization, Swedish Deep Stabilization Research Centre, 2002. Available from: https://www.sgi.se/globalassets/publikationer/svensk-djupstabilisering/sd-r9e.pdf

[32] "Effect of micro-sized quarry dust particle on the compaction and strength properties of cement-stabilized lateritic soil," Cleaner Materials, vol. 1, Art. no. 100023, 2021, Available from: https://doi.org/10.1016/j.clema.2021.100023

[33] F. Siregar, M. R. Saputra, A. Gaus, and I. Rauf, "Performance of Nickel Slag as a Stabilization Material for Soft Soil," South Asian Research Journal of Engineering and Technology, vol. 6, no. 1, pp. 29-34, 2024. Available from: http://dx.doi.org/10.36346/sarjet.2024.v06i01.004

[34] O. Cara?ca, "Soil improvement by mixing: techniques and performances," Energy Procedia, vol. 85, pp. 85-92, 2016. Available from: https://doi.org/10.1016/j.egypro.2015.12.277