ASEAN Engineering Journal

Full Paper

FLY ASH-BASED GEOPOLYMER FOR SUSTAINABLE SUBGRADE STABILIZATION: PHYSICAL AND MECHANICAL PROPERTIES

Woelandari Fathonah*, Rama Indera Kusuma, Enden Mina, Baehaki, Restu Wigati, Bella Rizka

Departement of Civil Engineering, Faculty of Engineering, Sultan Ageng Tirtayasa University, 42435, Cilegon City, Banten, Indonesia

Article history
Received
04 September 2024
Received in revised form
24 March 2025
Accepted
13 September 2025
Published online
28 February 2026

*Corresponding author
woelandari@untirta.ac.id

Graphical abstract

Abstract

Dynamic Cone Penetrometer (DCP) test carried out in Jalan Raya Kubang Laban, Serang Regency, shows that the location has soil-bearing capacity of 3.413%. Low soil bearing capacity can accelerate road damage and reduce efficiency, especially with high traffic. This percentage is lower than minimum California Bearing Ratio (CBR) of 6% needed for subgrade soil, according to Revised Road Pavement Design Manual No. 02/M/B/2017. Consequently, the problem was addressed by using fly ash geopolymer that chemically bond with soil particles to increase soil strength and contribute to waste management. Therefore, this research aimed to assess stabilization capacity of fly ash geopolymer and examine the effect on mechanical and physical properties of subgrade soil. To achieve the aim, several activator ratios were investigated, namely 10 Mol of NaOH with solution ratio of 2.0 (Na_2SiO_3 to NaOH), while the quantity of fly ash varied from 0% to 20%. Mechanical property were assessed using unconfined compressive strength (UCS) test at 0, 7, 14, and 28 days of curing. Meanwhile, physical and material characterization were examined using plastic limit, liquid limit, X-ray diffraction (XRD), and Scanning Electron Microscope-Energy Dispersive X-ray (SEM-EDX). The results showed that variation 3 (80% soil, 20% fly ash, S/L 1/2.5) had highest strength of 36.427 kg/cm^2 after 28 days with soil plasticity index (PI) of 6.88%, which meets the requirements for subgrade because it exceeds the minimum limit of 21–28 kg/cm² according to SNI 03-6887-2002. This research utilizes fly ash as an environmentally friendly construction material, supporting waste management and sustainable development with wide application potential.

Keywords: Fly ash, Geopolymer, Soil stabilization, Subgrade, Sustainable

1.0 INTRODUCTION

Soil is a combination of minerals, decomposed organic material, and generally loose sediments located on bedrock [1], [2], [3]. The presence of carbonates, organic matter, or oxides that settle between soil particles causes the bonds between soil grains to be relatively weak. Moreover, the spaces between these particles can contain water, air, or both.

Roads are routes used for vehicle transportation that play an important role in the daily activities of people. Relating to this definition, soil functions as a foundation for vehicle traffic and road structures. Soil attributes as well as its strength play a significant role in road construction planning particularly those properties which have an influence on the load supporting capacity of the soil used for construction. Moreover, subgrade soil is prone to moisture content and volume changes that may damage road construction, such as occurrence of potholes due to the instability of subgrade failure [4], [5].

Jalan Raya Kubang Laban, Terate Village, Kramatwatu Sub-district, Serang Regency, and Banten Province has a damaged road surface including potholes or erosion that seems to have extended to subgrade soil. In addition, there is an increased problem due to heavy vehicles, especially trucks that exert great pressure on both the road and the underlying soil. The field test conducted using Dynamic Cone Penetrometer (DCP) showed California Bearing Ratio (CBR) of 2.82% for subgrade soil. This value is below the standard set in Revised Pavement Design

Manual (2017) No. 02/M/B/2017, that subgrade CBR value should not be less than 6%. When CBR value is lower than the standard, then some measures need to be taken for stabilization of soil. In the context of this research, soil stabilization is achieved by adding chemical into the soil in order to improve mechanical and physical properties [3-7].

Geopolymer is a result of non-organic material's polymerization process [11]. This technology uses industrial waste, namely fly ash for geopolymer technology creation. To ensure easy production of geopolymer, source materials have to contain a significant amount of silica and alumina. For this purpose, the elements are dissolved using basic solutions such as sodium silicate (Na_2SiO_3) and sodium hydroxide (NaOH) to facilitate the chemical reaction. Fly ash waste can also be used in providing high amounts of silica and alumina. Generally, fly ash consists of small particles that are made up of alumina, silica, and iron [9-12]. Both amorphous and crystalline minerals are present in fly ash [13-14].

The addition of fly ash-based geopolymer to soil increased unconfined compression test (q_u) value [18]. However, this value is not consistent with soil that does not have geopolymer, at a proportion of 20% of the total sample. Research on soil without geopolymer showed smaller increase in q_u compared to those with geopolymer. Ground Granulated Blast Furnace (GGBS) can improve soil strength by taking precautions in order to avoid clay swelling. Based on the research, using 20% fly ash-based geopolymer produced q_u value of 15.09 kg/cm^2, only at 7 days. This result showed that q_u value was affected by the addition of geopolymer, leading to subgrade stabilization. This study uses type C fly ash which does not require curing with temperature variations due to its fast setting properties [11].

Previous research found that q_u value increased with longer days of curing. This is the reason that the best comprehensive strength could be achieved by using 10 Mol NaOH solution at ratio of 2.0 (NaOH to Na_2SiO_3) [11]. In addition, the highest q_u value was achieved by using 20% fly ash at the ratio of soil mixture with fly ash to activator solution (S/L) in variations of 1/1, 1.5/1, 2/1, 2.5/1, and 3/1, with the optimum being 1.5/1. UCS strength in fly ash-based geopolymer stabilized soils improved by increasing molarity of actuator from 8 M to 10 Mol [11].

Several activator concentration were examined in this research, ranging from 10 Mol NaOH with liquid-to-solid ratio (LSR) of 2.0 (Na_2SiO_3 to NaOH). Also, fly ash content of 0% and 20% was used together with variations of S/L ratio (fly ash to alkaline activator) of 1/2 and ½ which were tested at 0, 7, 14, and 28 days.

This study presents an approach that varies the ratio of Na_2SiO_3 and NaOH and the ratio of fly ash to activator, which has yet to be widely explored in previous studies. This approach is expected to improve the strength of the subgrade and provide a more environmentally and economically friendly solution, along with the increasing amount of fly ash waste generated by the industry.

2.0 METHODOLOGY

Materials such as soil, fly ash type "C", and alkali activators NaOH and Na_2SiO_3 were prepared in this research [16-17]. Soil and fly ash were dried, mixed homogeneously, and spread evenly. The specific materials used in this context could be seen in Figure 1.

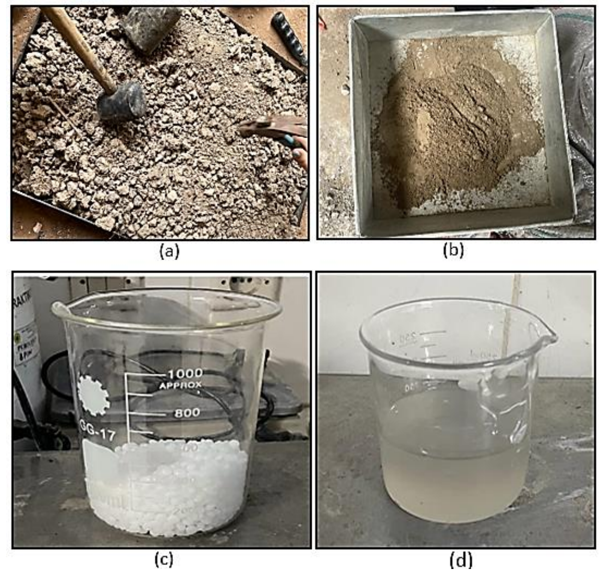

Figure 1 (a) Soil, (b) fly ash, (c) NaOH, (d) Natrium silicate

The soil and fly ash mixture were mixed until it was blended, then geopolymer mixture was prepared by adding alkaline activators (NaOH and Na_2SiO_3). Alkali activator is prepared by mixing NaOH and Na_2SiO_3 solutions according to a certain ratio, where NaOH solution is made by dissolving NaOH pellets in water and left for 24 hours for stabilization. Na_2SiO_3 solution is then added gradually while stirring until homogeneous. The mixture of soil and fly ash that has been stirred evenly is mixed with alkali activator slowly until the desired consistency is achieved. In the next phase, the mixture was placed in a cylindrical mold with 38 mm diameter and 76 mm height. The combination was compressed firmly to experience q_u using the standard Proctor method and the sample was removed from the mold using an extruder and wrapped in plastic to keep it wet. To obtain optimum strength, curing was carried out by incubating the samples at room temperature for 3, 7, 14, and 28 days. Furthermore, q_u was conducted using SNI 3638:2012 standard [21], to determine the optimum stress measured at 15% axial strain if the sample does not show a clear failure point. In this study, the stress value taken is the maximum value at the failure point identified from the stress-strain curve. The unconfined compressive strength testing apparatus is shown in Figure 2.

Figure 2 Unconfined Compression Strength (UCS) test

Liquid and plastic limit analyses were conducted on clay soil using SNI standard operating methods [19-20]. In this research, morphology was carried out with Scanning Electron Microscope (SEM) while phase analysis used X-ray diffractometer after applying a thin gold coating to the samples using a sputter coater. These processes were structured to determine the way in which geopolymer affected the mechanical and physical characteristics of soil, as well as the composition and morphology of the final geopolymer material. The range of additives used in this research could be seen in Table 1.

Table 1 Sample variation

Sample Variation	Soil	Fly Ash (S)	S/L	
			S (Fly Ash)	L (Alkali Activator)
(1)	100%	0%	1	0
(2)	80%	20%	1	2
(3)	80%	20%	1	2.5

3.0 RESULT AND DISCUSSION

3.1 Phisycal Properties Of Soil

Table 2 showed the test results for the physical characteristics of the original soil used in this exploration. According to Table 2, the clay compaction test produced optimal moisture content and dry density values of 27.786% and 1.14 g/cm^3. The original soil had PI of 20.18% and was categorized as organic clay soil with medium to high plasticity (OH) by Unified Soil Classification System (USCS) based on ASTM D2487-17. A soil is categorized as organic clay or organic silt if its oven-dry liquid limit is less than 75% of the liquid limit of the original test specimen, according to the procedure in ASTM D2217. Moreover, fly ash filled in the spaces between soil particles with tiny particles might increase the stability and compressive strength.

Table 2 Physical properties of the original soil

No	Properties	Value	Unit
1	Analysis of grain size (pass sieve no.200)	50.60	%
2	Specific gravity	2.490	-
3	Liquid limit	53.00	%
4	Plastic limit	32.82	%
5	Compaction		
	-Optimum water content	27.786	%
	-Maximum dry density	1.140	g/cm^3

3.2 Phisycal Properties of Mixed Soil (Soil with Fly Ash-Based Geopolymer)

Figure 3 showed the liquid and plastic limit values decreased as geopolymer variation increased, due to cation exchange, flocculation, and particle agglomeration processes in the clay soil. The incorporation of fly ash binder into the soil released calcium ions (Ca^{2+}), which were exchanged with sodium ions ($Na+$) present in the clay particles. This ion exchange process was known as cation exchange which caused many physical changes in the soil. This statement is supported by research conducted by Van Jaarsveld et al. (2003), which explains that the cation exchange process, including calcium and sodium exchange, can affect the physical properties of fly ash-based geopolymer materials, such as reducing the liquid limit and plastic limit values of the soil [24]. PI value showed the expansion and shrinkage properties of soil, and as the value increased, these properties increased. In this exploration, the original soil at Jalan Raya Kubang Laban, Terate Village, Kramatwatu Sub-district, Serang Regency, and Banten Province had PI of 20.18%, in variation (2) (80% soil, 20% fly ash, S/L ½) the value was 9.32%, and in variation (3) (80% soil, 20% fly ash, S/L 1/2.5), PI was 6.88%. Additionally, the incorporation of fly ash-based geopolymer in the test led to a decrease in PI. As a result of this process, the original soil which initially had a medium shrinkage potential, showed a reduced PI, lowering it to a lower development potential.

According to Highway Development Implementation Regulations of the Department of Public Works, PI standard for subgrades was < 15%. The soil samples containing fly ash and geopolymer were used as subgrade for roads, according to Atterberg limit results. This process showed that the strategy was successful in lowering PI of clay soil [25].

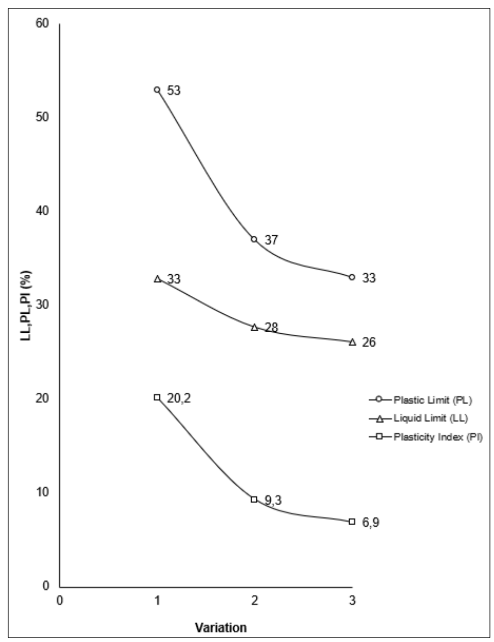

Figure 3 Results of liquid limit and plastic limit test

3.3 Mechanical Properties of Mixed Soil (Soil with fly ash-based geopolymer)

The impact of adding fly ash-based geopolymer on raising q_u value was shown in Figure 4. Increasing curing time contributed to a further increase in q_u. Test data showed that geopolymer addition had significant impact on q_u in soil, with highest value of 36.427 kg/cm^2 observed in variation (3) at 28 days. This value signified that the original soil has been increased by 3122.76% (Variation (1) 0-day curing) from the initial q_u of 1,096 kg/cm^2. An incident occurred when fly ash and alkaline activator reacted under alkaline activation, resulting in CASH (calcium-aluminate-silicate-hydrate) gel. The reaction between fly ash and alkali activator produces calcium-aluminate-silicate-hydrate (CASH) gel, which increases the strength and stability of geopolymer materials. This process occurs through the polymerization of silicates and aluminates under alkaline conditions, resulting in a strong matrix structure. Davidovits (1991) explained that CASH gel is formed during geopolymerization and strengthens the material [26], while Van Jaarsveld et al. (1996) and Lloyd & Rangan (2010) also confirmed the important role of CASH gel in improving the performance of fly ash-based geopolymer concrete [27], [28]. The expansion of soils and binding of particles as geopolymer were maintained by SiO_2, Al_2O_3, CaO, and Fe_2O_3 which were among the components of fly ash. Fine particles in fly ash filled the space between soil particles, leading to high q_u values. q_u value in variation (3) after 0 days of curing was lower compared to the original soil [11]. This process might be because the variation contained a high level of alkaline activator (liquid) and geopolymer mixture had not yet hardened at 0-day, leaving the soil in a soft state at the 0-day stage.

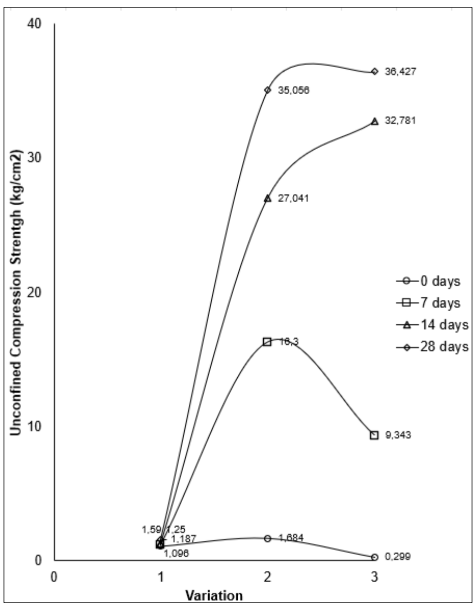

Figure 4 The effect of q_u value to mixture variation

Figure 5 showed the cracking in UCS test samples, and as the curing time increased from 7 to 28 days, the strength and stability of the soil-based geopolymer material improved significantly. This result was evident from the reduction in size and number of cracks in the sample. After 7 days, large and widespread cracks occurred due to the incomplete hydration process, while at 14 days, the cracks began to decrease as the structure of the material stabilized. On day 28, the material showed a few small cracks, signifying that the material had reached its maximum strength, with a denser structure and more resistant to cracking. The value obtained in variation 3 (80% soil, 20% fly ash, S/L 1/2.5) shows the highest strength of 36.427 kg/cm² after 28 days, which meets the standard requirements for subgrade. This strength exceeds the minimum limit set by SNI 03-6887-2002, which is between 21–28 kg/cm². This study used type C fly ash at room temperature for the curing process, which is supported by Hardjito & Rangan (2005) who stated that even though it takes longer, the resulting geopolymer still achieves sufficient strength for civil engineering applications [29], as well as by Abdila et al. (2021) who showed that type C fly ash does not require curing with temperature variations due to its fast setting properties [11].

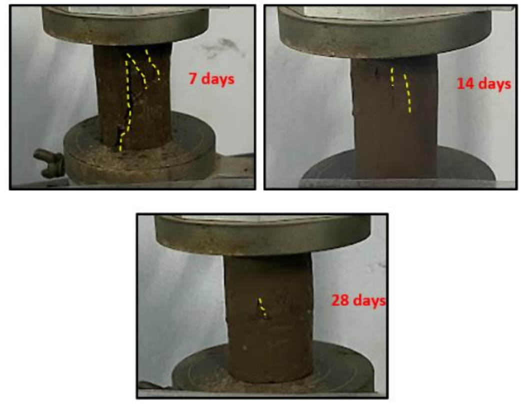

Figure 5 Cracking of UCS test sample

This study shows that a higher S/L ratio of 1/2.5 results in higher UCS values than a lower ratio. This indicates that increasing the amount of Na_2SiO_3 in the mixture can accelerate the formation of CASH gels, contributing to increased soil strength. These results are consistent with previous studies but provide a new contribution by showing that this higher ratio results in a more significant increase in strength at day 28. Research by Davidovits (1991) showed that increasing the S/L ratio can accelerate the formation of CASH gel, which contributes to increasing the strength of geopolymer materials . This is also supported by research by Lloyd & Rangan (2010), who observed that the addition of Na_2SiO_3 in the geopolymer mixture increased the strength of geopolymer concrete, especially at the age of 28 days [28].

3.4 Properties of Soil Mixed (Soil with fly ash-based geopolymer)

3.4.1 X-ray Diffraction (XRD) Analysis

Figure 6 showed an X-ray diffraction (XRD) graph of the soil sample mixed with fly ash-based geopolymer. The graph featured several sharp diffraction peaks, especially around 26-30 degrees 2θ, showing the presence of a crystalline phase such as quartz. Additionally, the pattern also showed an amorphous phase of geopolymer matrix, characterized by a diffuse archetype between the sharp peaks. Besides quartz, other crystalline phases of fly ash such as mullite might be present, while the contribution of natural soil minerals was also visible but less dominant [30]. This statement is supported by research by Van Jaarsveld et al. (1996) which showed that XRD on fly ash-based geopolymers indicated crystalline phases such as quartz and mullite, as well as amorphous phases of the formed geopolymer matrix [27]. Another study by Lloyd & Rangan (2010) also observed differences in crystalline and amorphous phases in geopolymers, which showed a transition from crystalline to amorphous structures during the alkali activation process[28].

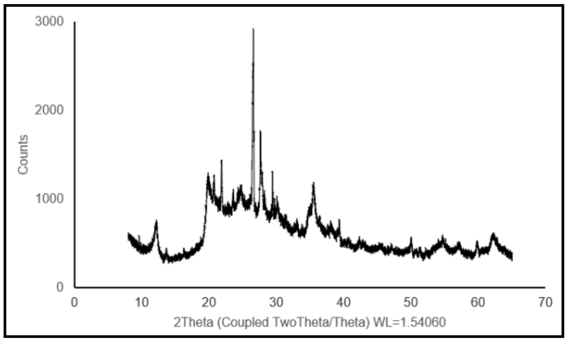

Figure 6 XRD test result

3.4.2 SEM-EDX Analysis

Figure 7 showed SEM test results of the soil sample mixed with fly ash-based geopolymer at 500x, 1000x, 2000x, and 5000x magnification. These images represented the details of microscopic structure of the mixture. In SEM images, spherical particles of a few micrometers in size were visible and were probably remnants of fly ash particles that did not fully react during geopolymer formation. These particles were embedded within a denser, irregular matrix, signifying that a significant portion of fly ash had interacted with the alkaline activator to form geopolymer structure. The image also showed a rough and irregular texture surrounding the particles, indicating the presence of an amorphous phase of geopolymer, and the aggregation of other small particles. This formation implied that the material had a heterogeneous composition, consisting of residual fly ash particles in geopolymer matrix.

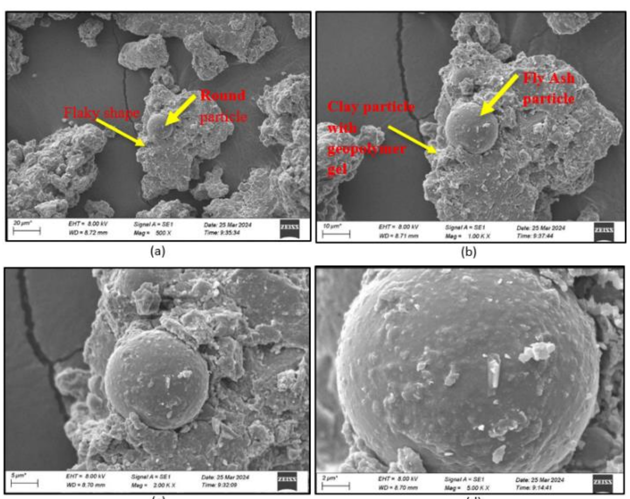

Figure 7 SEM-EDX result soil-based geopolymer with fly ash : (a) magnification 500x, (b) magnification 1000x, (c) magnification 2000x, (d) magnification 5000x

Fly ash was added to soil-based geopolymer to improve the strength when compared to soil-based geopolymer from soil alone. Relating to this discussion, Figure 8 showed the results of an Energy Dispersive X-ray Spectroscopy (EDX) test on a soil sample mixed with fly ash-based geopolymer. This examination implied that oxygen (44.22%) and silicon (18.66%) had the highest peaks, showing the predominance of silicate and alumina from fly ash as well as reflecting the structure of geopolymer.

The presence of these elements reflected the composition of fly ash and soil, as well as the success of geopolymerization process that incorporated the elements into geopolymer matrix. This process was related to previous research [11], [31].

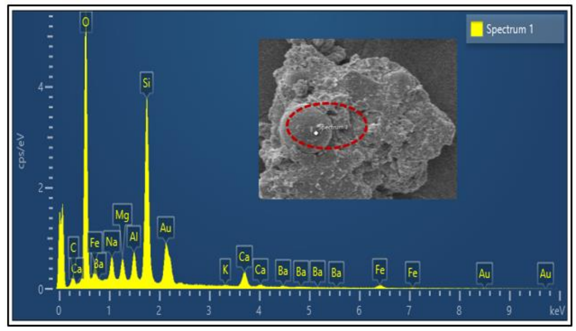

Figure 8 EDX result (Spectrum 1)

The research showed that incorporating fly ash into geopolymer material significantly increased soil strength. Using a mixture of 80% soil and 20% fly ash, with an S/L ratio of 1.5, the exploration achieved a significant q_u after 28 days of curing and a substantial reduction in PI. This reduction confirmed that soil mixed with fly ash could produce highly durable geopolymer materials with strong potential for practical applications in sustainable construction.This study is in line with the study of Van Jaarsveld et al. (2003) which showed that the addition of fly ash in geopolymers can increase the compressive strength and reduce the plasticity index of the soil, which indicates an increase in the quality of the material[24].

4.0 CONCLUSIONS

1. The addition of fly ash-based geopolymer effectively reduced the PI value of the soil, with the PI value of the mixture reaching 9.32% and 6.88%, meeting the criteria for subbase material.
2. Increasing the S/L ratio causes a decrease in the liquid limit and PI, and increases the plastic limit, which contributes to soil strengthening.
3. Variation 3 (80% soil, 20% fly ash, S/L 1/2.5) achieved the highest strength qu value of 36.427 kg/cm² after 28 days, exceeding the minimum limit of 21–28 kg/cm² according to SNI 03-6887-2002 for subgrades.
4. The novelty of this research lies in the effect of S/L ratio on increasing subgrade soil strength, demonstrating the potential of fly ash-based geopolymer as an environmentally friendly solution for sustainable construction.

Acknowledgements

The authors are grateful to Sultan Ageng Tirtayasa University for funding this research through Internal Grant in 2024.

Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper

References

[1] H. C. Hardiyatmo, 2019. *Mekanika Tanah* 1(7). Gadjah Mada University Press

[2] R. Yuliet and F. Leo Fernandez, 2012. "Pengaruh Penggunaan Semen Sebagai Bahan Stabilisasi Pada Tanah Lempung Daerah Lambung Bukit Terhadap Nilai Cbr Tanah," *Jurnal Rekayasa Sipil*, 8 (1): 29-44

[3] S. Setyanto, I. Iswan, and H. D. Rahmad, 2015. "Studi Kekuatan Batu Bata Pasca Pembakaran dengan Menggunakan Bahan Additive Serbuk Gergaji Kayu," *Jurnal Rekayasa*, 19 (2): 371–381.

[4] W. Fathonah, R. I. Kusuma, E. Mina, and N. D. Hasanah, 2023. "Sustainable Soil Stabilization Using Marble Dust Waste on High Plasticity Soils: Physical and Mechanical Properties Study," *International Journal of Applied Science and Engineering*, 20(4): 1–10, DOI: 10.6703/IJASE.202312_20(4).008.

[5] S. Feranie, A. Tohari, I. Karmila, and A. D. Puspitasari, 2023. "Penerapan Metode GPR dan Geoteknik pada Kajian Jalan, Jembatan, dan Lereng: Review," *Jurnal Sains dan Edukasi Sains*, 6 (2): 51–64.

[6] N. Cristelo, S. Glendinning, L. Fernandes, and A. T. Pinto, 2013. "Effects of Alkaline-Activated Fly Ash and Portland Cement on Soft Soil Stabilisation," *Acta Geotechnica*, 8(4): 395–405, DOI: 10.1007/s11440-012-0200-9.

[7] N. Cristelo, S. Glendinning, L. Fernandes, A. Teixeira Pinto, and U. P. Teixeira, 2012. "Effect of Calcium Content on Soil Stabilisation with Alkaline Activation," *Construction and Building Materials*, 29: 167–174, DOI: 10.1016/j.conbuildmat.2011.10.049.

[8] T. Kamei, A. Ahmed, and K. Ugai, 2013. "Durability of soft clay soil stabilized with recycled bassanite and furnace cement mixtures," *Soils and Foundations*, 53 (1): 155–165, DOI: 10.1016/j.sandf.2012.12.011.

[9] Z. Nalbantoğlu, 2004. "Effectiveness of class C fly ash as an expansive soil stabilizer," *Construction and Building Materials*, 18(6): 377–381, DOI: 10.1016/j.conbuildmat.2004.03.011.

[10] M. Zhang, H. Guo, T. El-Korchi, G. Zhang, and M. Tao, 2013. "Experimental feasibility study of geopolymer as the next-generation soil stabilizer," *Construction and Building Materials*, 47: 1468–1478.

[11] S. R. Abdila et al., 2021. "Evaluation on the mechanical properties of ground granulated blast slag (GGBS) and fly ash stabilized soil via geopolymer process," *Materials*, 14(11): 2833, DOI: 10.3390/ma14112833.

[12] S. K. Das and Y. Yudhbir, 2005. "Geotechnical characterization of some Indian fly ashes," *Journal of Materials in Civil Engineering*, 17(5): 544–552.

[13] E. T. Brown, B. P. McMahon, V. K. Dhir, and P. J. Hobbs, 1987. "Geotechnical practice for waste disposal," in R. D. Woods (Ed.), *Geotechnical Practice for Waste Disposal*. New York: American Society of Civil Engineers.

[14] A. Fernández-Jiménez, A. Palomo, and M. Criado, 2005. "Microstructure development of alkali-activated fly ash cement: A descriptive model," *Cement and Concrete Research*, 35(6): 1204–1209.

[15] S. Horpibulsuk, C. Phetchuay, A. Chinkulkijniwat, and A. Cholaphatsorn, 2013. "Strength development in silty clay stabilized with calcium carbide residue and fly ash," *Soils and Foundations*, 53(4): 477–486, DOI: 10.1016/j.sandf.2013.06.001.

[16] Z. Pan, L. Dongxu, Y. Jian, and Y. Nanru, 2003. "Properties and microstructure of the hardened alkali-activated red mud–slag cementitious material," *Cement and Concrete Research*, 33(9): 1437–1441.

[17] P. Narayanan, C. K. Mouli, and V. D. Kumar, 2018. "Pulse velocity test on banana fibre concrete with nano silica," *International Journal of Civil Engineering and Technology*, 9 (11): 2853–2858.

[18] O. C. Debanath, A. Rahman, M. A. Rahman, and S. M. Farooq, 2019. "Use of fly ash based geopolymer for stabilization of expansive soil," in *Proceedings of the 9th International Conference on Geotechnique, Construction Materials and Environment*, Tokyo. [Online]. Available: https://www.researchgate.net/publication/338516811, Retrieved June 5, 2024.

[19] F. Winnefeld, A. Leemann, M. Lucuk, F. P. Svoboda, and M. Neuroth, 2010. "Assessment of phase formation in alkali activated low and high calcium fly ashes in building materials," *Construction and Building Materials*, 24 (6): 1086–1093.

[20] S. Rios, N. Cristelo, A. Viana da Fonseca, and C. Ferreira, 2016. "Structural performance of alkali-activated soil ash versus soil cement," *Journal of Materials in Civil Engineering*, 28(2): 04015125, DOI: 10.1061/(ASCE)MT.1943-5533.0001398.

[21] Badan Standardisasi Nasional, 2012. *SNI 3638:2012 – Metode Uji Kuat Tekan Bebas Tanah Kohesif*. Jakarta.

[22] Badan Standardisasi Nasional, 2008. *SNI 03-1967-2008 – Cara Uji Penentuan Batas Cair Tanah*. Jakarta.

[23] Badan Standardisasi Nasional, 2008. *SNI 03-1966-2008 – Cara Uji Penentuan Batas Plastis dan Indeks Plastisitas Tanah*. Jakarta.

[24] J. G. S. Van Jaarsveld, J. S. J. Van Deventer, and G. C. Lukey, 2003. "The characterisation of source materials in fly ash-based geopolymers," *Materials Letters*, 57: 1272–1280.

[25] S. Z. S. Zaliha, A. M. M. Al Bakri, H. Kamarudin, and A. Fauziah, 2015. "Characterization of soils as potential raw materials for soil stabilization application using geopolymerization method," *Materials Science Forum*, 803: 135–143, DOI: 10.4028/www.scientific.net/MSF.803.135

[26] J. Davidovits, 1991. "Inorganic polymeric new materials," *Journal of Thermal Analysis and Calorimetry*, 37 (8): 1633–1656.

[27] J. G. S. Van Jaarsveld, J. S. J. Van Deventer, and L. Lorenzen, 1996. "The potential use of geopolymeric materials to immobilise toxic metals part I: Theory and applications," *Amazing World of Science*. [Online]. Available: www.geopolymer.org, Retrieved June 8, 2024.

[28] N. A. Lloyd and B. V. Rangan, 2010. "Geopolymer concrete with fly ash," in *Proceedings of the Second International Conference on Sustainable Construction Materials and Technologies*.

[29] D. Hardjito and B. V. Rangan, 2005. "Development and properties of low-calcium fly ash-based geopolymer concrete," *Research Report*, Curtin University of Technology.

[30] P. Risdanareni, P. Puspitasari, and E. J. Jaya, 2016. "Chemical and physical characterization of fly ash as geopolymer material," *MATEC Web of Conferences*, 78: 01021.

[31] P. S. Parhi, L. Garanayak, M. Mahamaya, and S. K. Das, 2018. "Stabilization of expansive soils using alkali activated fly ash," in *Handbook of Advances in Characterization and Analysis of Expansive Soils and Rocks*. Berlin/Heidelberg: Springer.