

Effect of fly ash on the strength properties of cohesive soils for roadbed reinforcement

Trang-Nhat Tran^{1,*}, Duc-Trung Tran², Nguyet-Duyen Lam³

¹Transportation Engineering Faculty, Can Tho University;

²Civil Engineering Faculty, Can Tho University;

³Faculty of Engineering, Kien Giang University;

*Corresponding author: ttnhat@ctu.edu.vn

■ Received: 25/05/2025 ■ Revised: 23/06/2025 ■ Accepted: 20/08/2025

ABSTRACT

The reinforcement of cohesive soils for roadbed construction is critical to ensure long-term stability and performance of transportation infrastructure. This study explores the effect of fly ash, a byproduct of coal combustion, on the strength properties of cohesive soils, aiming to improve their suitability for use in roadbed applications. Laboratory experiments were conducted by mixing fly ash in varying proportions (ranging from 10% to 50% by weight) with locally sourced cohesive soil. Key geotechnical tests, including unconfined compressive strength (UCS), Maximum Dry Density, Atterberg limits, and compaction characteristics, were performed to evaluate changes in strength and consistency. Results indicated that the addition of fly ash led to a significant increase in UCS, especially at 20–35% fly ash content, suggesting improved load-bearing capacity and structural integrity. Furthermore, the plasticity index was reduced, and optimum moisture content slightly increased, reflecting favourable modifications in soil behaviour. These improvements are attributed to pozzolanic reactions between fly ash and soil particles, leading to the formation of cementitious compounds. The study concludes that fly ash is an effective and sustainable stabilizing agent for cohesive soils, offering both environmental and engineering benefits for roadbed reinforcement and broader civil engineering applications.

Keywords: cohesive soil, Atterberg limits, Standard proctor, Unconfined Compressive Strength.

1. INTRODUCTION

The integrity and longevity of road infrastructure depend significantly on the quality of the subgrade, which serves as the foundational support for the entire pavement system [1]. In many geographical regions, particularly in developing countries, cohesive soils such as clay are commonly encountered as subgrade materials [2]. While these soils are abundant and easy to work with, they often exhibit poor engineering properties, including low shear strength, high plasticity, poor drainage, and high compressibility [3]. These characteristics can lead to several issues in road construction, including differential settlement, shrinkage and swelling with moisture fluctuations, and overall reduced load-bearing capacity [4]. Consequently, roadbeds constructed over untreated cohesive

soils are more susceptible to deformation and premature failure under traffic loading and environmental stresses [5].

To mitigate these challenges, soil stabilization techniques are employed to improve the engineering behavior of weak soils [7]. Among the various methods available, chemical stabilization using industrial by-products has gained prominence due to its cost-effectiveness and environmental advantages [8, 10]. One such material is fly ash, a fine particulate residue generated from the combustion of pulverized coal in thermal power plants. Rich in silica, alumina, and other oxides, fly ash, it can react with calcium hydroxide in the presence of water to form cementitious compounds [9, 42]. These reactions improve the bonding between soil particles and contribute to an overall enhancement in soil strength and durability [6].

The use of fly ash in soil stabilization offers several benefits. Firstly, it transforms a waste material into a valuable construction resource, contributing to sustainable development and reducing the environmental burden associated with its disposal [12]. Secondly, fly ash is widely available and relatively inexpensive, making it an economically attractive option for large-scale applications. Thirdly, when appropriately mixed with soil and other stabilizing agents such as lime or cement, fly ash can significantly improve the strength, workability, and water resistance of cohesive soils. This makes it particularly suitable for roadbed reinforcement, where improved mechanical performance is crucial for long-term serviceability [11].

Previous studies have indicated that the effectiveness of fly ash in enhancing soil properties depends on several factors, including the type of soil, the class and composition of fly ash, the dosage used, and the curing conditions. In general, Class C fly ash, which contains higher levels of calcium, is more reactive and thus more effective in stabilization compared to Class F fly ash [12]. Additionally, the optimal percentage of fly ash for maximum strength gain typically ranges between 15% and 25%, depending on the specific characteristics of the soil and project requirements [8, 13].

Fly ash is widely used in construction due to its siliceous or aluminosiliceous composition, which gives it cementitious properties. In its finely divided form, and in the presence of moisture, fly ash reacts chemically with calcium hydroxide at normal temperatures to form compounds with binding characteristics [16-19].

The primary goal of this study is to assess the performance of soil after incorporating different percentages of fly ash as an admixture and to explore the efficient use of fly ash as a replacement material in soil stabilization [9].

2. EXPERIMENTAL INVESTIGATION

Laboratory tests were carried out using natural clay soil sourced from the southern

region Taiwan. The fly ash used in the study, classified as Class F, was obtained from the Taoyuan town, Taiwan. Although Class C fly ash is generally more reactive due to its higher calcium content and inherent self-cementing properties, Class F fly ash was selected for this study based on its wide availability in the local region, environmental considerations (lower carbon footprint), and its compatibility with lime-treated cohesive soils. Additionally, the study aims to evaluate whether sufficient mechanical improvement can be achieved using Class F fly ash in roadbed applications, particularly when used in combination with optimal moisture content and compaction energy, thereby promoting sustainable reuse of industrial by-products. Various random proportions of fly ash were mixed with the soil to determine the optimum percentage that enhances the strength characteristics of the clayey soil [20]. The properties of the materials used and the details of the tests conducted are provided below.

2.1. Materials and Properties

The properties of the clayey soil and Fly ash in Table 1, 2

Table 1: Properties of clay

Properties	Values
Specific Gravity	2.6
Differential free swell %	40
LL%	54.8
PL %	20.67
PI	34.13
BIS classification	CH

Table 2: Properties of Fly ash

Properties	Values
Specific Gravity	2.1
Bulk density g/cm ³	1.06
PI	NP
Absorption (%)	1.3

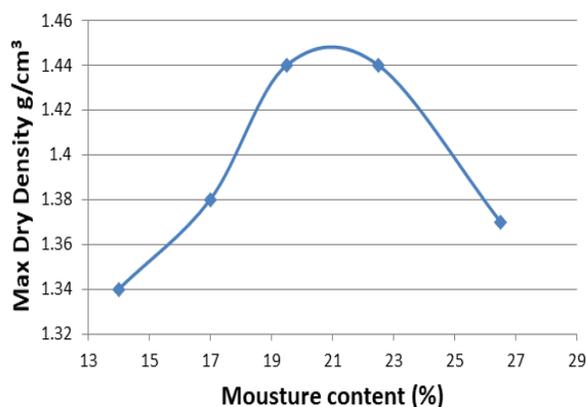


Figure 1. Standard proctor test for Control sample

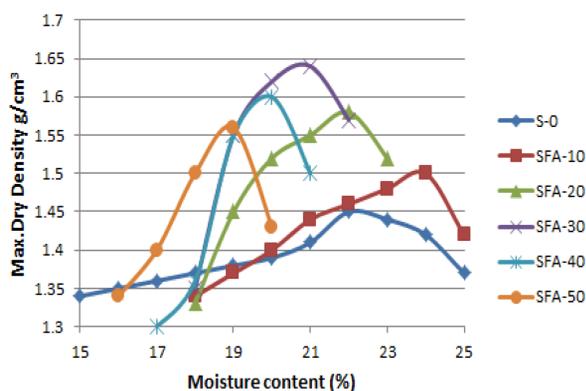


Figure 2. Standard proctor test for Fly ash proportions

2.2. Laboratory Test on Soil Stabilised with Fly ash

2.2.1. Standard Proctor’s Compaction Test

Standard Proctor tests were performed both with and without the addition of fly ash to determine the maximum dry density and the corresponding optimum moisture content. Fly ash was added to the dry soil in varying proportions of 10%, 20%, 30%, 40%, and 50% [7-8]. The results obtained from these tests for each percentage of fly ash are presented in Table 3. Figure 1 illustrates the relationship between dry density and moisture content for the control sample, while Figure 2 displays the dry density and moisture content values for the soil mixed with different percentages of fly ash, in comparison to the control sample. In addition, the Standard Proctor Compaction Test is a laboratory method used to determine the optimum moisture content (OMC) at which a soil type will become most dense and achieve its maximum dry

unit weight. It is widely used in geotechnical engineering to design and control earthworks and foundations. To establish the relationship between moisture content and dry density of soil and find the Optimum Moisture Content (OMC) and Maximum Dry Density (MDD) for compaction.

A compaction curve is generated. The curve usually rises, peaks (at OMC), then falls as excess water displaces soil solids and reduces dry density. The progress of Compaction: Mechanical densification of soil by reducing air voids.

Table 3: Standard Proctor test results for various proportions of Fly ash

S.No	Soil composition	OMC(%)	MDD (g/cm ³)
1	Soil	22.0	1.45
2	Soil + 10% Fly ash	24	1.50
3	Soil + 20% Fly ash	22.1	1.57
4	Soil + 30% Fly ash	20.8	1.64
5	Soil + 40% Fly ash	20.0	1.60
6	Soil + 50% Fly ash	19.0	1.56

2.2.2. Unconfined compressive strength test

Figure 3 shows a set of cylindrical soil specimens, likely prepared for Unconfined Compressive Strength (UCS) testing or curing as part of a soil stabilization study [21]. The tray contains 8 cylindrical specimens, each wrapped in plastic film (likely to prevent moisture loss during curing). Each cylinder appears to be labelled, possibly indicating different mix ratios (e.g., fly ash percentages), sample IDs, or curing durations. Beside, the specimens are placed on a metal or plastic tray, typically used for laboratory storage during the curing period. The black caps or tops might be used to seal the top surface or protect it from contamination and evaporation. Soil samples stabilized with varying percentages of fly ash, prepared for strength testing such as UCS. Being cured under controlled conditions,

possibly for 7, 14, or 28 days [6, 8]. 28 days is the time which access standard benchmark for strength evaluation Part of a study related to roadbed reinforcement or soil improvement using industrial byproducts like Class F fly ash [14, 39].



Figure 3. Some samples preparing compression test

Cylindrical specimens were prepared using the optimum water content determined from the Standard Proctor test. These specimens were then subjected to major principal stress until failure occurred due to shearing along a critical failure plane. The test was repeated for different percentages of fly ash added to the soil. This procedure helps identify the percentage of additive that results in the highest load-bearing capacity. Figure 4 presents the plot of compressive strength versus strain for the control soil sample, while Figure 5 illustrates the compressive strength and strain values for various fly ash proportions compared with the control sample [24].

Curing time also played a critical role, with UCS values showing substantial improvement between 7 and 28 days due to on going some internal reactions [27-29]. A curing period of 7 days is used to evaluate the early development of strength, while a 14-day period represents an intermediate stage to monitor the progression of strength gain. The results suggest that fly ash can be effectively used to stabilize highly compressible clays, improving their load-bearing capacity and reducing long-term deformation risks in subgrade layers [30-32]. The findings indicate that fly ash is particularly effective in stabilizing highly compressible clay soils. By

incorporating appropriate percentages of fly ash and allowing adequate curing time, these soils exhibit enhanced load-bearing capacity and greater resistance to deformation. Such improvements are crucial for subgrade layers in road construction, where long-term performance and structural integrity are essential. The use of fly ash not only helps mitigate the inherent weaknesses of soft clays but also offers a sustainable alternative to traditional stabilization methods. Therefore, optimizing both the dosage of fly ash and the curing duration is vital to maximizing the benefits of fly ash stabilization in infrastructure applications.

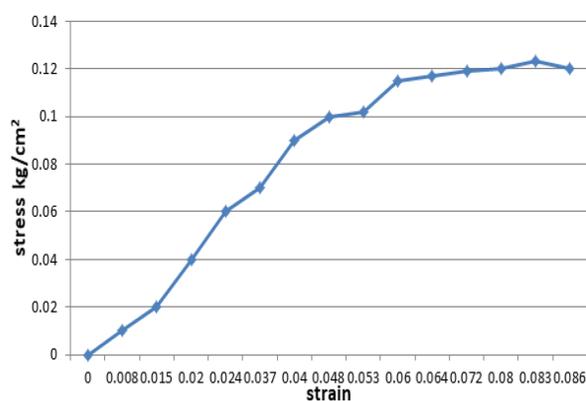


Figure 4. UCS test for Control sample

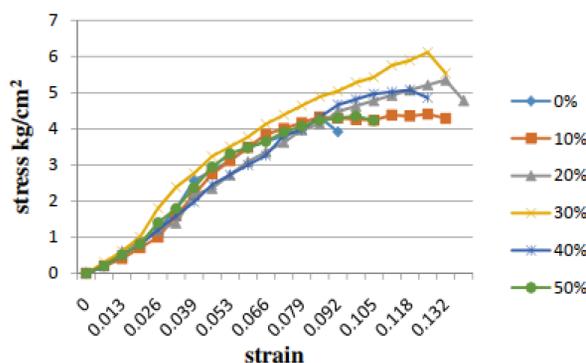


Figure 5. UCS test for Fly ash proportions

3. RESULTS AND DISCUSSION

This study demonstrates that the incorporation of Class F fly ash significantly improves the strength characteristics of cohesive soils, making it a viable additive for roadbed reinforcement applications. The Standard Proctor test was used to determine the optimum moisture content and maximum dry density of expansive soil

mixed with varying percentages of fly ash (0%, 10%, 20%, 30%, 40%, and 50%). Figure 6 illustrates the variation in maximum dry density and optimum moisture content with different fly ash contents. The results show that both maximum dry density and optimum moisture content increase with fly ash addition up to 30%, but begin to decrease gradually beyond this point. In the fly ash-treated soil, the optimum moisture content reduces from 24% to 19%, while the maximum dry density increases from 1.45 g/cm³ to 1.64 g/cm³. These findings indicate that adding fly ash significantly influences the compaction behavior of black cotton soil [25-26, 41].

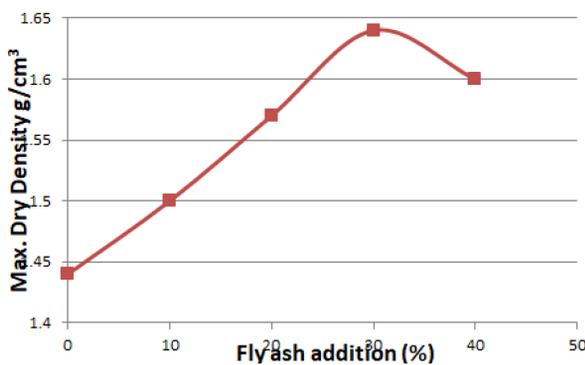


Figure 6. Comparison of dry density values with fly ash proportions

The results of the Unconfined Compression Test for different proportions of fly ash are presented in Figure 7. These results indicate that adding fly ash to clay soil triggers an internal reaction within the soil matrix, which contributes to an increase in shear strength. It has been observed that the strength characteristics of clay soil can be favorably improved through the addition of fly ash, with the most effective results achieved when fly ash is added in the range of 25% to 40% [28, 31, 33]. In addition, the use of fly ash not only enhances the geotechnical performance of weak cohesive soils but also supports sustainable construction practices by recycling industrial by products [22, 30]. Future studies should explore the combined use of fly ash with activators such as lime or cement to further optimize the stabilization process, especially at higher replacement levels [32, 34, 40].

4. DISCUSSION

Curing time is also a critical factor influencing strength development. In general, UCS values improve significantly between 7 and 28 days of curing, reflecting the ongoing formation of stable bonding products. Some studies indicate continued strength gain beyond 28 days, which is particularly notable in systems where Class F fly ash is used with lime. This long-term strength development is beneficial for the performance and durability of roadbeds. Over time, these reactions form cementitious compounds such as calcium silicate hydrate (C-S-H), which enhance particle bonding and result in improved soil structure [22].

Moreover, the California Bearing Ratio (CBR) values of fly ash-treated cohesive soils often show a marked increase, reflecting improved load-bearing of the subbase performance. This enhancement makes such treated soils more suitable as subgrade or subbase layers in pavement structures.

In terms of plasticity characteristics, the Atterberg limits showed a consistent trend: the liquid limit decreased slightly, the plastic limit increased, and the plasticity index (PI) decreased with higher fly ash content. A reduced PI is desirable as it implies decreased soil cohesiveness and plasticity, leading to better workability and lower susceptibility to shrink-swell behavior. These changes in plasticity characteristics enhance the performance of cohesive soils under varying moisture conditions, making them more stable over time.

The compaction behavior of the fly ash-treated soils also showed notable changes. While the maximum dry density tended to decrease slightly due to the lower specific gravity of fly ash compared to soil particles, the optimum moisture content generally increased. This shift suggests that fly ash-treated soils require more water to achieve

maximum compaction, which should be considered during field application to avoid compaction issues or over-saturation.

From an environmental and economic standpoint, the use of fly ash in soil stabilization offers substantial benefits. It recycles an industrial waste product that would otherwise require costly disposal and potentially pollute the environment. Furthermore, it reduces reliance on traditional stabilizing agents like cement and lime, both of which have high carbon footprints [37].

Totally, we confirm that fly ash is a viable and effective material for improving the strength properties of cohesive soils. The performance gains observed in this study validate its use in roadbed reinforcement applications [38]. However, careful consideration of the fly ash type, dosage, and curing time is necessary to maximize benefits. Long-term field studies, durability assessments are recommended to supplement laboratory findings and ensure reliable performance under real-world conditions.

5. CONCLUSION

The study on the Effect of Fly Ash on the Strength Properties of Cohesive Soils for Roadbed Reinforcement demonstrates the considerable potential of fly ash as a cost-effective and sustainable stabilizing agent for weak subgrade soils. The comprehensive laboratory investigation, which included unconfined compressive strength (UCS), Maximum Dry Density, Atterberg limits, and compaction tests, confirmed that the addition of fly ash leads to significant improvements in the strength and performance characteristics of cohesive soils.

In addition to strength improvements, fly ash incorporation modified the plasticity characteristics of cohesive soils. The plasticity index (PI) decreased with increasing fly ash content, indicating reduced soil

cohesion and improved workability. Lower plasticity implies that the treated soils are less susceptible to volume changes due to moisture variations, which is a common problem in natural cohesive soils and often leads to pavement cracking or heaving. These changes support the idea that fly ash-treated soils are more dimensionally stable and resilient under seasonal and climatic variations.

From a practical standpoint, fly ash-treated soils offer improved workability, reduced shrink-swell potential, and greater resistance to moisture-induced deterioration. These improvements result in more stable subgrades, reduced thickness of required pavement layers, and longer service life of road infrastructure.

From a broader perspective, the use of fly ash offers significant environmental and economic advantages. It promotes the reuse of industrial waste, reducing the need for landfilling and minimizing environmental contamination. Additionally, using fly ash in place of conventional stabilizers such as lime or cement helps reduce carbon emissions and construction costs. These benefits align with modern sustainable development goals, making fly ash a valuable component in green infrastructure initiatives.

This study confirms that its application enhances critical geotechnical properties and contributes to the development of more durable, sustainable pavements. However, successful implementation requires careful consideration of soil type, quality of soil type, fly ash characteristics, proper mix design, and adequate curing. Future research should focus on field-scale validations, the use of blended binders, and the long-term performance of stabilized soils under varying environmental conditions. With the right approach, fly ash can be a key material in designing and building resilient important transportation infrastructure.

REFERENCES

- [1] Gerrit Jordaan (2023), "Principles of Flexible Pavement Design Incorporating Nano Modified Emulsion (NME) Technologies for Optimising the use of Naturally Available Granular Materials", 13th Conference on Asphalt Pavements for southern Africa.
- [2] Sharma, R. S., & Sivapullaiah, P. V. (2016). "Improvement of subgrade characteristics of clayey soil using lime and cement", *Indian Geotechnical Journal*, 46(1), 84–91
- [3] Das, B. M. (2013), "Principles of Geotechnical Engineering (8th ed.)", Cengage Learning.
- [4] Lee D Jones (2024), "Expansive Soils", British Geological Survey.
- [5] Terzaghi, K., Peck, R. B., & Mesri, G. (1996), "Soil Mechanics in Engineering Practice (3rd ed.)". Wiley-Interscience
- [6] Cokca, E. (2001), "Use of class C fly ash for the stabilization of an expansive soil. *Journal of Geotechnical and Geoenvironmental Engineering*"
- [7] Hausmann, M. R. (1990), "Engineering Principles of Ground Modification", McGraw-Hill.
- [8] Kolias, S., Kasselouri-Rigopoulou, V., & Karahalios, A. (2005), "Stabilisation of clayey soils with high calcium fly ash and cement" *Cement and Concrete Composites*, 27(2), 301–313. <https://doi.org/10.1016/j.cemconcomp.2004.02.043>
- [9] Pandian, N. S. (2004), "Fly ash characterization with reference to geotechnical applications", *Journal of Indian Institute of Science*, 84(2), 189–216.
- [10] Sherwood, P. (1995), "Soil Stabilisation with Cement and Lime: State-of-the-Art Review", Transport Research Laboratory.
- [11] Naik, T. R., & Singh, S. S. (1997), "Fly ash generation and utilization—An overview". *Fly Ash for Soil Improvement*, ASCE Geotechnical Special Publication No. 69, 1–9.
- [12] FHWA (Federal Highway Administration). (2005), "Fly Ash Facts for Highway Engineers (FHWA-IF-03-019)", U.S. Department of Transportation.
- [13] Rai, A. K., Singh, S. K., & Kumar, A. (2014). "Utilization of fly ash and lime for stabilization of expansive soils for safe disposal" *International Journal of Environmental Research and Development*, 4(1), 49–56.
- [14] Ahmaruzzaman, M. (2010), "A review on the utilization of fly ash". *Progress in Energy and Combustion Science*, 36(3), 327–363. <https://doi.org/10.1016/j.peccs.2009.11.003>
- [15] Dharmendra Singh, February (2024) "Stabilization of Expansive Soil: A Review", *Innovation in Smart and Sustainable Infrastructure book*.
- [16] Cokca, E (2011), "Use of Class C fly ashes for the stabilization of an expansive soil", *Journal of Geotechnical and Geoenvironmental Engineering*, 127(7), pp.568-573.
- [17] Lin, B., Cerato, A.B., Madden, A.S., & Elwood Madden, M.E (2013), "Effect of Fly Ash on the Behavior of Expansive Soils" *Microscopic Analysis. Environmental & Engineering Geoscience*, 19(1), pp.85–94.
- [18] Lopes, L. S. E., Szeliga, L., Casagrande, M.D.T., & Motta, L.M.G (2012) "Applicability of Coal Ashes to be used for Stabilized Pavements Base" *GeoCongress 55 (21)*, 2562-7759.
- [19] Mirsa, A (2018) "Stabilization Characteristics of Clays Using Class C Fly Ash", *Construction and Building Materials*
- [20] A.B. Huang (2016), "Characterization of silt/sand soils", Geomechanics Society, Sydney, Australia.
- [21] ASTM D2166/D2166M-16. (2016). "Standard Test Method for Unconfined Compressive Strength of Cohesive Soil", ASTM International.
- [22] Nalbantoglu, Z. (2004), "Effectiveness of Class C fly ash as an expansive soil stabilizer", *Construction and Building Materials*. Volume 18, Issue 6, Pages 377-381.
- [23] Rahman, M. M., & Khan, M. S. (2020). Optimization of Soil to Fly-Ash Mix Ratio for Enhanced Engineering Properties of Clayey Sand for Subgrade Use. *Applied Sciences*, 10(20), 7038.

- [24] Farichah, H., Hutama, D. A., & Solin, D. P. (2023). Evaluation of the Strength Characteristic of Soil Stabilized with Fly Ash. *Jurnal Pensil: Pendidikan Teknik Sipil*, 12(3), 273–280
- [25] Sivapullaiah, P.V., Prashanth, J.P., Sridharan, A. (1996), “Effect of fly ash on the index properties of black cotton soil”. *Soils and Foundations*, 36(1), 97-103
- [26] Jeevanantham, V., Jayashree, J., & Magudeaswaran, P. (2016), “Influence of Fly Ash in Strength Characteristics of Expansive Soil”, *International Journal of Civil Engineering and Technology (IJCIET)*, 7(6), 67–76
- [27] Vizcarra1, G.O.C., Casagrande, M.D.T., & da Motta, L.M.G (2014). “Applicability of municipal solid waste incineration ash on base layers of pavements”. *Journal of Materials in Civil Engineering*
- [28] Pandian, N.S. (2004), “Fly ash characterization with reference to geotechnical applications”, *Journal of Indian Institute of Science*, 84, 189–216
- [29] Nalbantoglu, Z. (2014), “ Effectiveness of Class C fly ash as an expansive soil stabilizer,” *Construction and Building Materials*, 18(6), 377–381.
- [30] Phani Kumar, B. R., & Sharma, R. S. (2004), “Effect of fly ash on engineering properties of expansive soils” *Journal of Geotechnical and Geoenvironmental Engineering*, 130(7), 764–767.
- [31] Kolay, P. K., & Tiwari, A. K. (2011). “Improvement of geotechnical properties of silty clay with fly ash”, *International Journal of Earth Sciences and Engineering*, 4(6), 1028–1033.
- [32] Mir, B. A., & Sridharan, A. (2013), “Effect of fly ash on engineering properties of expansive soils”, *IOSR Journal of Mechanical and Civil Engineering*, 5(1), 20–25.
- [33] Amu, O. O., Ogunniyi, S. A., & Oladeji, O. O. (2011), “Geotechnical properties of lateritic soil stabilized with fly ash”, *American Journal of Scientific and Industrial Research*, 2(5), 673–677.
- [34] Muntohar, A. S., & Hantoro, G. (2017). “Influence of lime and fly ash on engineering properties of clayey soil”, *Journal of Engineering*, Vol.9, No.12.
- [35] Rahman, M. M., & Khan, M. S. (2020). “Optimization of Soil to Fly-Ash Mix Ratio for Enhanced Engineering Properties of Clayey Sand for Subgrade Use”, *Applied Sciences*, 10(20), 7038
- [36] Kaniraj, S. R., & Havanagi, V. G. (2001). “Behavior of cement-stabilized fiber-reinforced fly ash-soil mixtures”, *Journal of Geotechnical and Geoenvironmental Engineering*, 127(7), 574–584.
- [37] Rahman, M. M. (2023), “ Optimization of Soil to Fly-Ash Mix Ratio for Enhanced Engineering Properties of Clayey Sand for Subgrade Use ”, *Applied Sciences*, 10(20), 7038
- [38] AASHTO Guide for Design of Pavement Structures (1993, “Industry standard for pavement design in the U.S., including stabilized base/subbaselayers”
- [39] Cui, G., et al. (2024), “ Mechanical Properties and Neural Network Prediction of Cement–Fly Ash-Enhanced Roadbed Soil in Seasonal Frozen Zones Under Short-Term Curing”, *KSCE J Civ Eng*, 28, 106–123.
- [40] Huang, S., et al. (2023). “Experimental Study on the Road Performance of Phosphogypsum-Modified Lime-Fly Ash Stabilized Red Clay”, *Appl. Sci.*, 13(23), 12689
- [41] Munoz, Y. O., et al. (2023), “The Behavior of Stabilized Reinforced Soil for Road Embankments Application”, *Geotech Geol Eng*, 41, 2599–2628.
- [42] Ajay Kumar, (2023), “Study on the Characterization and Classification of Fly Ash Samples Obtained Locally”, ISSN 2694-997.