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Strength Improvement of Dredged Marine Soil as Road Subgrade Material using Fly Ash and Cement: Evaluation and Mix Ratio Optimization

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Abstract

Dredged Marine Soil (DMS) is considered improper for use as a subgrade in roads due to high moisture content, low strength, and inability to withstand load. Additionally, there are concerns about the environmental aspects of disposing of DMS, thus necessitating the search for appropriate methods for sustainable use. Stabilization of soils with fly ash (FA) and cement has attracted interest as an alternative to upgrading existing soils, with reduced use of conventional materials. This research explores the use of FA and cement to upgrade DMS, enhance its properties, and determine suitable mix ratios for subgrade construction in highways. Experiments in the laboratory involved DMS, both natural and stabilizing, with mixtures of FA and cement in ratios that give varying contents of these substances. The experimental methods involved Atterberg limit tests, Hydrometer tests, Specific gravity, Proctor compaction, Unconfined Compressive Strength (UCS), and California Bearing Ratio (CBR). Scanning Electron Microscopy (SEM) was also used to determine the microstructure, particularly the chemical composition and bonding properties. Curing times of 1, 3, and 7 days are considered when assessing the effect on the developed strengths. The result indicated that the amended DMS lacked sufficient strength and bearing capacity, thereby reaffirming that it cannot be used as subgrade material. But stabilization with FA and cement helped attain better results, especially with extended curing times. FA:Cement mix with a 50:50 ratio demonstrated strength beyond 400kPa and load-bearing capacity more than 20%, as specified by the Public Works Department (JKR). SEM analysis showed that the microstructure was denser and had lower void content, confirming that the cementation process was responsible for the enhanced strength. Finally, using FA and cement to stabilize subgrade material is a viable alternative for sustainable subgrade construction on highways.

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1. Introduction

Rapid coastal developments and expansion at various ports have resulted in an unprecedented increase in dredging activities, consequently producing large quantities of DMS. DMS generally possesses high water content, low shear strength, and poor bearing capacity [1]. Hence, DMS cannot be used directly in geotechnical and road construction. Consequently, DMS is often disposed of at offshore dumping sites or in confined land areas, increasing project costs and raising environmental concerns [2]. Recently, as part of sustainable development in civil engineering, the reuse of DMS as a construction material has attracted increasing interest.

DMS without stabilization has poor engineering properties, with low strength and load-bearing capacity and high compressibility, making it unsuitable for use as a subgrade material in road construction. To overcome these constraints, cementitious materials were used in soil stabilization. It has been noted that cementation increases soil strength through hydration reactions, although the use of large amounts of cement is costly and environmentally hazardous [3]. Therefore, another cementitious material, FA, generated by combustion, has emerged as a supplemental material in some soil stabilization methods.

Literature has shown that FA exhibits pozzolanic activity, reacting with calcium sources to enhance soil strength through secondary cementitious action. Different authors have explained that the combined use of FA and cement leads to the improvement in compacted characteristics, increased strength and load-bearing capacity for UCS and CBR values, and enhancement in long-term strength development because of cementitious product development, especially because of the main compound, C–S–H [4] [5]. Among all the FA, it has also been noted that Class C FA exhibits self-cementing properties, hence providing additional strength to the stabilized soil. Still, the stability performance of FA–cement-stabilized DMS strongly depends on mix proportions, curing periods, and soil types, which warrants further experimental evaluation.

Thus, this research aims to investigate the effectiveness of FA and cement in enhancing the engineering properties of DMS for possible use as a road subgrade material. Through an analysis of soil properties, strength behavior, and bearing capacity, this research aims to establish an optimal FA-cement mix that meets the minimum requirements set by JKR in Malaysia [6]. The results of this research are hoped to be beneficial in ensuring that the construction industry embraces sustainability by reducing dependence on current DMS disposal techniques.

2. Materials and Methods

In this study, the materials used and the experimental processes for testing the efficiency of FA and cement as stabilization agents for DMS in road subgrade construction are discussed. It may be seen that the material test processes selected here have been executed with a focus on aligning them with the framework defined for this research study. In fact, this chapter introduces the first essential step in determining the efficiency of the selected stabilization agent for the purpose defined here. This initial step involves knowledge of the materials selected for the experiment, such as DMS, FA, and OPC cement. Furthermore, each experimental process for determining the physical, compaction, strength, and bearing properties of the soils, as initially obtained, has been executed in accordance with the defined British Standard (BS) parameters.

2.1 Materials Used

Table 1 presents three major materials to study the stabilization of DMS suitable for subgrade construction. The major material used was fine-grained DMS, generally obtained from Endau-Rompin, Johor, and characterized by high moisture content and low strength [1].

Table 1 *Materials used in the study*

Material	Description	Function
Dredged Marine Soil (DMS)	Fine-grained marine soil	Base material
Fly Ash (FA)	Class C fly ash	Pozzolanic stabilizer
Cement	Ordinary Portland Cement	Binder and early strength

Two stabilization materials were used to upgrade the properties of DMS. These were cement and FA. Class C FA is a material with good pozzolanic properties and was used as a stabilizer to enhance long-term strength and sustainability. Ordinary Portland Cement (OPC), which exhibits good hydration properties, serves as the primary binding material in this study to achieve early strength gain through hydration. Overall, the selection of DMS, Class C FA, and OPC cement provided the essential base and stabilizing materials required to systematically evaluate the strength improvement of DMS for road subgrade applications.

2.2 Methodology

The methodology includes desk research followed by the making of raw materials such as natural DMS, FA, and cement. Experimental work was broadly categorized into two phases. Phase 1 included the analysis of the chemical composition of the FA with the use of SEM and the test for the physical properties of the DMS with various soil tests like Atterberg limit, specific gravity, hydrometer test, Proctor compaction test, and Unconfined Compression Strength (UCS), as specified in the British Standards (BS 1377). Phase 2 included the stabilization test, covering the FA-to-cement mixing ratio and the cure period. Testing for strength improvement was conducted using UCS and CBR tests on the mixture with the ratio that meets the 400 kPa strength requirement for the subgrade.

2.3 Experimental Procedure

In this study, DMS was stabilized with FA and Ordinary Portland Cement (OPC), and distilled water was used in the mixing process. Raw soil was prepared to be air-dried, pulverized, and sieved before mixing with FA and cement at predetermined weight ratios of 100:0, 75:25, 50:50, 25:75, and 0:100, compacted into molds, and cured at room temperature (25°C) for 1, 3, and 7 days. Several laboratory tests were conducted, including Atterberg limits, specific gravity, hydrometer analysis, Proctor compaction, UCS, and CBR, to evaluate the improvement in strength and durability. At the same time, SEM was performed to describe the microstructure of FA. All results have been compared with unstabilized DMS to determine the optimum FA–cement mix ratio that meets JKR standards for subgrade soil, based on UCS ≥ 400 kPa and CBR ≥ 20%, and to assess the feasibility of using FA–cement stabilization as a sustainable option in road construction. Table 2 tabulates the experimental procedures summary of this study.

Table 2 *Experimental procedure summary*

Step	Material/ Equipment	Procedure	Purpose
Sample preparation	DMS, FA, cement, distilled water	Dry, sieve, weigh, mix binders with soil	Ensure uniform test specimens
Mix ratios	FA:OPC (100:0, 75:25, 50:50, 25:75, 0:100)	Blend binders by weight of soil	Compare stabilization performance
Curing	Plastic wrap, room temperature (25°C)	Cure specimens for 1, 3, 7 days	Allow hydration & pozzolanic reaction
Soil characteristics	Casagrande cup, pycnometer, hydrometer, Proctor mould	Atterberg limits, specific gravity, particle size, compaction	Establish baseline properties of untreated DMS
Strength tests	UCS moulds, compression machine, CBR apparatus	UCS and CBR tests on treated samples	Evaluate strength & bearing capacity
Microstructure	SEM with EDS	Imaging and chemical analysis of FA	Identify chemical composition & reaction potential

Together, these procedures ensured a systematic evaluation of DMS stabilization, from raw material characterization through to strength and microstructural assessment.

2.4 Characteristics and Test Parameters

System characterization was performed to outline the identified parameters, the apparatus used, and the method employed in the analytical process to confirm that the experimental system was operating effectively. System characterization was performed using physical and mechanical parameters for both the unstabilized and stabilized DMS.

Physical property testing included Atterberg limit tests and hydrometer tests to determine the soil type based on its consistency and composition [7]. Proctor compaction behavior testing was conducted to determine the maximum dry density (MDD) and the optimum moisture content (OMC) of the soil. Mechanical property testing included the UCS and the CBR test to determine the strength properties of the stabilized soil. SEM testing

Progress in Engineering Application and Technology Vol. 7 No. 2 (2026) p. 68-76

was conducted to determine the soil's microstructural reactions and verify the cementation reactions that occurred [8].

The results of the two methods have confirmed that the stabilization system worked properly. The improvement in strength, as shown in Table 3 by the indices corresponding to void reduction and matrix bonding, demonstrates that the experimental setup and methods were valid for investigating the performance of the stabilized DMS.

Table 3 *Summary of characteristics tests and measurement parameters*

Test	Parameter Measured	Purpose
Atterberg Limits	LL, PL, PI	Soil classification
Hydrometer Analysis	Particle size	Fine content evaluation
Proctor compaction	MDD, OMC	Sample preparation
UCS test	Compressive strength	Strength evaluation
CBR test	Bearing ratio	Subgrade suitability
SEM Analysis	Microstructure	Stabilization mechanism

These characterization and testing parameters collectively provided a reliable basis for evaluating the physical, mechanical, and microstructural performance of the stabilized DMS.

3. Results and Discussion

The data analysis strategy adopted in this study consisted of both quantitative and qualitative approaches to ensure a comprehensive evaluation of the experimental results. The results are presented in tables and graphs to effectively communicate the influence of FA and cement additives on soil strength. Major observations regarding the soil's strength and carrying capacity, based on measurement results, have been addressed.

3.1 Properties of Unstabilized DMS

The physical properties of unstabilized DMS were determined to assess its suitability for use as road subgrade material. The Atterberg limits for unstabilized DMS are presented in Table 4, which give a liquid limit (LL) of 24.31%, plastic limit (PL) of 19.86%, and plasticity index (PI) of 4.45%. These values indicate low plasticity, while the corresponding USCS classification is ML (low plasticity silt).

Table 4 *Atterberg limit results of untreated DMS*

Property	Results
Liquid Limit (LL)	24.31%
Plastic Limit (PL)	19.86%
Plasticity Index (PI)	4.45%
Soil Classification	ML (Low plasticity silt)

Additionally, an examination of the hydrometer test result, as shown in the particle size distribution curve, confirms that most particles are in the fine silt size range, thus making the material poorly drained and low in shear strength. It is thus evident that unstabilized material is not ideal for use in road subgrades. These Atterberg limit results confirm that the untreated DMS is a low plasticity fine-grained soil, underscoring the need for stabilization before it can be considered for subgrade use.

3.2 Proctor Compaction

The results indicate the optimum moisture content (OMC) and maximum dry density (MDD), showing how compacted the soil can be in the ground. Those values are also referenced by comparing them with stabilized samples to assess the effectiveness of FA treatment in improving compact properties and overall soil performance. The compaction characteristics of untreated DMS for dry density vs moisture content are summarized in Table 5. The relatively low maximum dry density and high optimum moisture content observed

were typical of fine-grained marine soils with high natural moisture content.

Table 5 *Compaction characteristics of untreated DMS*

Parameter	Value
Maximum Dry Density, MDD	1.92 g/cm3
Optimum Moisture Content, OMC	19.32%

The average value of the three samples gives an MDD of 1.90 g/cm^3 and an OMC of 19.32%. With a relatively high OMC, small deviations in water content during compaction result in noticeable reductions in dry density. This makes the soil more sensitive to improper water control during construction. Soils with moderate MDD and high OMC will likely perform less well under heavy traffic than other soils with higher density and lower OMC, unless stabilized with additives [10]. Whereas average parameter values indicate that the soil can be compacted to a stable state, the high OMC and moderate MDD highlight certain limitations regarding strength, water demand, and sensitivity to moisture control. These disadvantages suggest that soil stabilization or blending with stronger materials, such as FA and cement, may be necessary for demanding engineering applications, such as road subgrades. These compaction results confirm that the untreated DMS requires careful moisture control, supporting the case for further improvement through FA and cement stabilization.

3.3 Unconfined Compressive Strength (UCS)

Fig. 1 shows the UCS values for both unstabilized and stabilized DMS after 7 days. The maximum UCS recorded, that is, 419.20 kPa, was obtained for the 50:50 FA and cement mix, which exceeded the minimum requirement of 400 kPa as specified by JKR for subgrade materials.

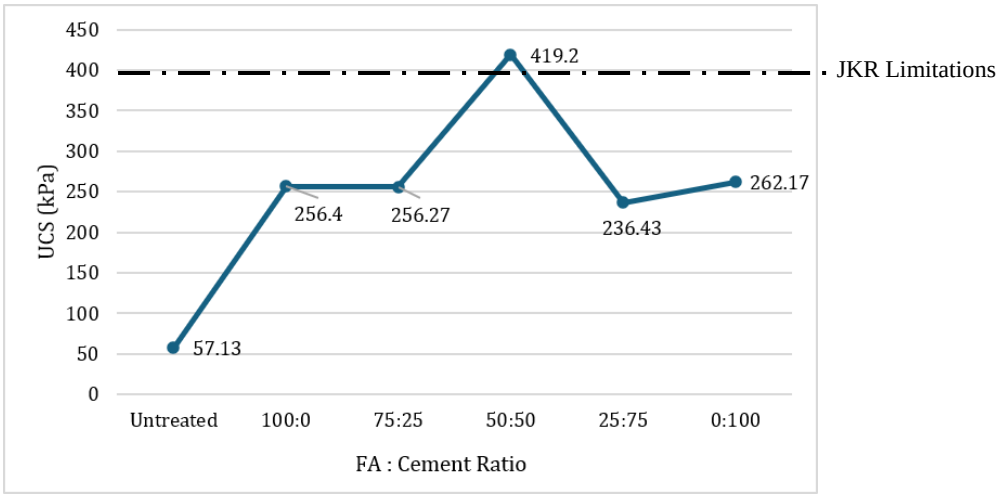


Fig.1 *UCS results of stabilized DMS at different FA:Cement ratio*

The remaining proportions, such as 100:0, 75:25, 25:75, and 0:100, showed moderate increases, ranging from 236 kPa to 262 kPa. The observed results firmly establish that stabilization is critical for DMS, with the 50:50 FA-cement mix offering the best stabilization treatment for subgrade failure.

3.4 Scanning Electron Microscopy (SEM)

The elemental composition of FA was characterized using SEM–EDS and is summarized in Table 6. From the analysis, oxygen, calcium, and silicon were the dominant elements, while aluminum, carbon, magnesium, iron, potassium, and sodium were detected in trace amounts. Relatively high calcium content suggests that the FA is rich in calcium-based compounds. While the results from SEM–EDS are elemental rather than oxide compositions, the significant calcium content suggests a very high CaO content within the material. BS EN 451 states that FA with more than 20% weight CaO is regarded as Class C FA, which corresponds to reports found in literature [12]. Based on the determined elemental abundance, the FA used in this study should be considered Class C, derived from sources such as sub-bituminous or lignite coal and known for its self-cementing properties.

Progress in Engineering Application and Technology Vol. 7 No. 2 (2026) p. 68-76

Table 6 *Elemental of fly ash*

Element	Ca	Si	O	Al	Mg	C	Fe	K	Na
Weight (%)	28.91	10.96	47.83	3.67	1.62	4.41	1.32	0.70	0.58

The surface characteristics of FA particles examined through SEM, illustrated in Fig. 2, appear to be porous and irregular. This indicates that the FA type is Class C. The porous nature of FA enhances interlocking, bonding, and void filling during soil stabilization. The porous nature also improves the surface area, an essential parameter in cementation and pozzolanic reactions in soil. In a related study, a high CaO content in Class C FA was found to be responsible for the earlier stabilization of soil strength reported by [13]. The microscopic features provide an explanation for the effective enhancement of DMS strength observed in this study.

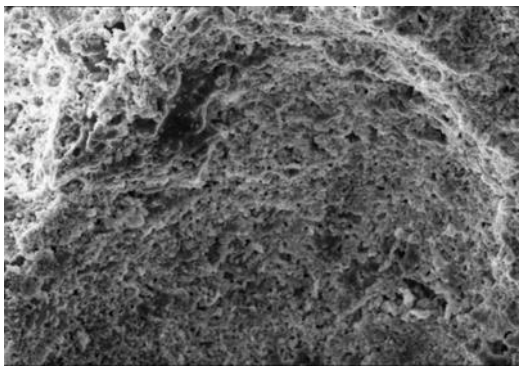


Fig. 2 *Porous and surface morphology of typical FA particles*

These microstructural observations reinforce the elemental analysis, confirming that the porous morphology of the Class C FA plays a key role in the strength gains achieved through stabilization.

3.5 California Bearing Ratio (CBR)

The California Bearing Ratio (CBR) test was conducted on DMS stabilized with a 50:50 FA-cement mixture, in accordance with BS 1377: Part 4:1990 guidelines. The results, shown in Fig. 3, indicate that both the top and bottom layers of the stabilized soil achieved load-bearing values above the minimum requirement of 20% for subgrade materials as specified in JKR/SPJ/1988-S4.

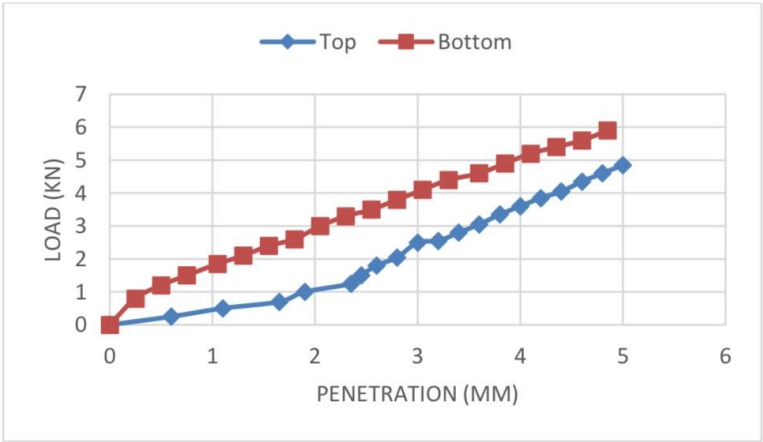


Fig. 3 *Load-Penetration curves of CBR*

For the bottom layer, load-bearing values ranged from 26.29% to 29.38% at penetrations of 2.50 mm and 5.00 mm, slightly higher than the top-layer values of 24.04%–25.15%. This difference is attributed to better compaction in the bottom layer. Overall, the stabilized DMS meets the strength requirement of above 20% for use as subgrade material. The stabilized soil is suitable for roads with light to medium traffic. For heavier traffic,

a thicker subbase layer is recommended to ensure proper load distribution. The use of DMS with FA–cement stabilization also reduces reliance on natural materials, supporting sustainable and environmentally responsible construction practices [14].

3.6 Discussion

The test results confirmed that the DMS exhibited poor engineering properties, rendering it unsuitable for use as a road subgrade material. Analysis of the test on the unstabilized soil indicated that it comprised a fine-grained material, had a moderate specific gravity, a high optimal moisture content, and a low unconfined compressive strength, which indicated low bearing capacity. Improvement occurred following stabilization with FA and cement. The FA showed porous, irregularly shaped particles that contributed significantly to bonding and void-space filling within the soil [15]. There were improvements in compaction characteristics, with a high maximum dry density and decreased sensitivity towards moisture [16]. There were also improvements in strength properties, with the 50:50 FA-cement mixture recording a UCS strength of 419.20 kPa, meeting the JKR standards. Furthermore, the CBR values for both the top and bottom were above 20%, indicating that the treated soil met the subgrade material requirement.

The improvement in strength and load-bearing capacity may be attributed to the synergistic action of cement hydration and pozzolanic reactions involving FA. Cement hydration contributed to the early development of strength, while long-term gain was due to the formation of secondary cementitious products, mainly C-S-H [17]. The presence of Class C FA still enhanced self-cementation, resulting in a denser soil structure. The 50:50 FA-cement mixture had the best combination of calcium material, reactive silica, and alumina, yielding superior performance. Testing in accordance with JKR standards confirmed that this mixture met the minimum strength and bearing capacity requirements, ensuring that stabilized DMS can be reused safely as a subgrade material for a road while supporting sustainable construction [18].

4. Conclusion

In this study, DMS was found unsuitable for road construction due to its higher moisture content, lower shear strength, and lower bearing capacity. Stabilization with the addition of FA and cement significantly improved strength and load-bearing capacity, the extent of which was proportional to the curing time. The mixture was established as 50% FA and 50% cement to achieve a strength above 400 kPa and a load-bearing capacity above 20%, meeting the requirements set by the JKR for classified soil types as subgrades for road construction. Results were further validated by SEM examination, which showed greater CaO interconnectivity in type C fly ash for stabilized soil samples. In all, the objectives of the study, which involved determining FA composition, assessing stabilization performance, and identifying the optimum mix ratio, were addressed. Future work should extend curing periods to 56 days to capture the long-term durability and optimize binder ratios by increasing FA content, reducing cement usage, and ensuring sustainable yet technically sound soil stabilization practices [18].

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

This journal requires that all authors take public responsibility for the content of the work submitted for review. The contributions of all authors must be described in the following manner:

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Nurul Umie Zarifah Yusoff and Salina Sani;* ***data collection:*** *Nurul Umie Zarifah Yusoff;* ***analysis and interpretation of results:*** *Nurul Umie Zarifah Yusoff and Salina Sani;* ***draft manuscript preparation:*** *Nurul Umie Zarifah Yusoff, Salina Sani, Anis Ayuni Suied. All authors reviewed the results and approved the final version of the manuscript.*

References

[1] Long, C. (2024). *Quality Testing and Engineering*. Quality Testing and Engineering, Inc. Retrieve from https://qteinc.com/common-soil-problems-inconstruction-and-how-testing-helps-solve-t h e m .

[2] Abidi, I., Benamara, L., Correia, A. a. S., Pinto, M. I. M., & Cunha, P. P. (2021). Characterization of dredged sediments of Bouhanifia dam: potential use as a raw material. *Arabian Journal of Geosciences*, *14*(23). https://doi.org/10.1007/s12517-021-08742-4

[3] Prasad. (2022). *Complete guide to soil cement stabilization, its benefits*. Structural Guide. https://www.structuralguide.com/soil-cement-stabilization/

[4] Kumar, D., & Daniyal, M. (2025). Application of industrial supplementary cementitious materials in concrete: A Review. *Journal of Civil Engineering and Applications*, *6*(1), 126–135. https://doi.org/10.22271/27078388.2025.v6.i1b.44

[5] Gautam, L., Purbe, M. K., Sharma, K. V., Kumar, C., & Kalita, P. P. (2025). Environmental impact mitigation and durability enhancement of concrete through fly ash substitution: a comprehensive review. *Journal of Building Pathology and Rehabilitation*, *10*(2). https://doi.org/10.1007/s41024-025-00609-5

[6] *Jabatan Kerja Raya* (2024). https://www.scribd.com/document/397778015/66807469-JKR-Manual-on-Pavement-Design-pdf

[7] Hossain, M. S., PhD PE, Islam, M. A., Badhon, F. F., & Imtiaz, T. (2021). *Atterberg Limit test*. Properties and Behavior of Soil-Online Lab Manual. https://uta.pressbooks.pub/soilmechanics/chapter/atterberg-limit-test/

[8] Herrero, Yanet Rodríguez, et al. "Characterization of Biobased Materials." *Advanced Applications of Biobased Materials*, 2023, pp. 111–143, www.sciencedirect.com/topics/materials-science/scanning-electron-microscopy, https://doi.org/10.1016/b978-0-323-91677-6.00005-2.

[9] Ali, A., Zhang, N., & Santos, R. M. (2023). Mineral characterization using Scanning Electron Microscopy (SEM): A review of the fundamentals, advancements, and research directions. *Applied Sciences*, *13*(23), 12600. https://doi.org/10.3390/app132312600

[10] Spagnoli, G., & Shimobe, S. (2020). An overview on the compaction characteristics of soils by laboratory tests. *Engineering Geology*, *278*, 105830. https://doi.org/10.1016/j.enggeo.2020.105830

[11] Ramya, L. (2024). Significance of 7-Day Concrete strength, Performance and Quality Control. *Civil Engineering Blitz*. https://civilenggblitz.com/7-day-concrete-strength/

[12] Turan, C., Javadi, A. A., & Vinai, R. (2022). Effects of Class C and Class F Fly ash on mechanical and microstructural Behavior of Clay Soil—A Comparative Study. Materials, 15(5), 1845. https://doi.org/10.3390/ma15051845

[13] Wardhono, A. (2018). Comparison Study of Class F and Class C fly ashes as cement replacement material on strength development of Non-Cement Mortar. IOP Conference Series Materials Science and Engineering, 288, 012019. https://doi.org/10.1088/1757-899x/288/1/012019

[14] Sambre, T., Endait, M., & Patil, S. (2024). Sustainable soil stabilization of expansive soil subgrades through lime-fly ash admixture. *Discover Civil Engineering*, *1*(1).

[15] John, E., & Lothenbach, B. (2023). Cement hydration mechanisms through time – a review. *Journal of Materials Science*, *58*(24), 9805–9833. https://doi.org/10.1007/s10853-023-08651-9

[16] Ji, E., Xu, F., Wei, H., Qian, W., He, Y., & Zhu, P. (2022). An investigation on Mineral Dissolution and Precipitation in Cement-Stabilized Soils: Thermodynamic modeling and Experimental analysis. *Applied Sciences*, *12*(14), 6843. https://doi.org/10.3390/app12146843

[17] Kushwaha, E. R. (2025b). California Bearing Ratio (CBR) Explained: Importance, Testing & Applications - Civil Tutorials. *Civil Tutorials*. https://civiltutorials.com/california-bearing-ratio/

[18] Ho, L. S., Van Quang, L., Van-Pham, D., & Huynh, T. (2025). Strength development and microstructural characterization of eco-cement paste with high-volume fly ash. *Results in Engineering*, *26*, 105013. https://doi.org/10.1016/j.rineng.2025.105013