Research Article

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Strength Characteristics of Bentonite Nano Clay Stabilized with Addition of Lime, Fly Ash and Silica Fume for Soil Environmental Sustainability

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ABSTRACT

The suboptimal engineering characteristics, including low tensile strength and significant compressibility volumetric changes, are the significant challenges faced during the construction of sub-structures in expansive Soil. The instability of the sub-structure leads to the settlement of the structure and compromises its safety and endurance. This paper explores how Bentonite Nano Clay (BNC) reacts with varying proportions of lime, fly ash, and silica fume. The ratios used for these additives were 2%, 4%, and 6%. The compaction characteristics and the stress-strain curve were analyzed. Incorporating silica fume into BNC leads to a decrease in both the liquid limit and the plasticity index. Concurrently, this addition increases the plastic limit of the clay. As the percentage of silica fume in the mixture rises, there is a corresponding decrease in the maximum dry unit weight and an increase in the optimum moisture content. Additionally, the introduction of silica fume contributes to an increase in the free swell but also it has an increase in the swelling pressure of clay. These results suggest that silica fume stabilization is an effective method for treating expansive clay.

Keywords: Expansive soil; Bentonite nano clay; Lime; Fly ash; Silica fume; Stabilization.

1. INTRODUCTION

The main features of expansive soils and how they affect construction work is that they are mostly made of clay minerals, especially montmorillonite, which can let in and let out water. When expansive soils get wet, they grow and bulge, putting a lot of pressure on foundations, pavements, and structures. On the other hand, when they dry up, they shrink which can lead to structural damage due to the soil's movement. The challenges involved in the construction of structures at expansive soils are settlement of structures, bumping of roads, and low bearing capacity. Structures may collapse if expansive soils are not handled properly and may cause injuries and fatalities. Stabilization requires a high set of skills for the engineers to reduce risks. Numerous materials can do the stabilization of soil. Lime can be considered as one of the stabilizing agents. There is a need to conduct consolidation tests and grouting techniques that give better results in soil stabilization (Al-Gharbawi *et al.* 2022).

The quality of the expansive clay soil has been improved considerably when sodium silicate with hydrated lime powder was used as a stabilizer. The California Bearing Ratio value increased significantly compared to the untreated soil when an optimal combination of lime and sodium silicate was used (Dharini *et al.* 2023). The experiment by Raja *et al.* (2022) discussed the optimal percentage of RHA and lime sludge to use for stabilization purposes. Integrating an ideal amount of lime improves the properties of black cotton soil, enhancing its suitability for construction showing decreases in index properties and increases in unconfined strength tests. In addition to that, quarry dust was used separately and with lime. It showed increase in unconfined compressive strength (UCS) (Anand *et al.* 2021). The use of geopolymer for the binding purpose was studied briefly along with industrial wastes such as fly ash and GGBFS. Fly ash and GGBFS were used as stabilization agents (Abdila *et al.* 2022). Two different fly ash were used with lime to study the plasticity and workability of clayey soil. It was found that the soil was less sticky, less plastic, and more workable than unstabilized soil. The combination of lime and fly ash initiated a decrease in the porosity of the soil (Deepak *et al.* 2021). The clayey soil was treated with fly ash of varying percentages. The samples were dried for 28 and 90 days and the strength was analyzed. The quality of clay was enhanced by the addition of marble dust and fly

ash, which are known to stabilize and strengthen the soil. In another work, different qualities of marble dust and fly ash were used. It proved that the environmentally friendly way of stabilization (Zorluer *et al.* 2014). Mir *et al.* (2013) utilized two distinct types of fly ash, each with a different calcium content. The findings indicated a preference for the fly ash variant with a higher calcium content due to its beneficial properties. The variable blends of two different soils were used and the results showed that the fly ash greater than 25% we less significant (Seyrek, 2018). The combination of fly ash and ceramic wastes was experimented. The results showed that the blend was better than the individual components (Sharma, 2020).

The study of using sugarcane and bagasse ash in untreated expansive soils showed the improved geopolymer gel production and less toxicity. These results paved a new eco-friendly way of increasing the stability of clayey soils (Ramezani *et al.* 2023). The stabilization of soft Karolin clay was done using SF and ESA of various percentages. It showed the reduction of specific gravity, plasticity, and dry density. The shear strength was also improved significantly than untreated soil (Hasan *et al.* 2021). The swelling pressure of soil decreases when treated with silica fume in the range of 0 to 10%. The addition of silica fume also leads to an increase in optimum moisture content and a decrease in maximum dry density. Furthermore, cohesion increases with silica fume content, contributing to enhanced soil strength (Singh *et al.* 2020). The combined use of polypropylene fiber and silica fume promotes mechano-chemical stabilization of clayey soil, improving its engineering performance (Tiwari *et al.* 2019). The stabilization of clayey soil using lime with 4% silica fume highlights the occurrence of pozzolanic reactions in both soil–lime and soil–silica fume systems (Alrubaye *et al.* 2017). Similarly, mixtures of silica fume, fiber, and lime in expansive soils, evaluated over a curing period of 28 days, show significant improvements in mechanical properties such as UCS and resistance to freeze–thaw effects (Saygili *et al.* 2019). Bentonite nanoclay (BNC) treated with limestone and hydrated lime in the range of 0–10% shows a reduction in both swell pressure and swelling potential. The swelling potential decreases from 34.5% to approximately 26.5% and 1% for clay samples treated with 10% limestone and 10% hydrated lime, respectively. While limestone reduces the strength of the clay, hydrated lime significantly improves it. The addition of lime and fly ash has a notable influence on soil behaviour. Lime reduces the free swell index by improving workability and decreasing plasticity. In contrast, fly ash enhances pozzolanic reactivity, thereby reducing swelling pressure and swelling potential and improving overall engineering properties. Furthermore, the inclusion of fly ash contributes to a reduction in swell pressure and swelling potential. Compaction characteristics and unconfined compressive strength (UCC) improve at 4% lime content but decrease when the lime content is increased to 6% (Phanikumar et al. 2020).

Clay stabilized with lime, cement, and alkali-activated binders (AAB), reinforced with fibers such as polypropylene, glass, hemp, and coir fibers, showed enhanced mechanical performance. The strength of AAB-stabilized soil was 35–40% higher than that of conventional lime- and cement-treated soils. However, the study also indicated that slag and fly ash contents may contribute to volumetric instability and the development of tensile cracks in clay soils (Syed *et al.* 2022).

Taki *et al.* (2020) compared soils treated with lime and rice husk ash (RHA). The unconfined compressive strength (UCS) values were measured after curing periods of 0, 3, 7, 21, and 28 days. The results showed that RHA reduced the strength of the soil due to the presence of coarser particles, whereas lime-treated soil exhibited UCS values approximately three times higher than those of RHA-treated clay. It was also observed that shear strength decreased when stabilizer content exceeded the optimum dosage. In another study, fly ash was used at proportions of 10%, 20%, 40%, 60%, and 80%. The results indicated that the swelling potential decreased by about 40%. Fly ash significantly altered the strength characteristics of black cotton (BC) soil through pozzolanic reactions, leading to strength enhancement. For highly reactive fly ash, the pozzolanic effect dominated over the silty behaviour, whereas for less reactive fly ash, the silty nature had a greater influence. Shenal Jayawardane *et al.* (2020) investigated the effect of lime and fiber addition on the expansibility and compressibility of marine clay. Coir fiber (CF) and polypropylene fiber (PPF) were incorporated at varying contents of 0.5%, 1%, 1.5%, and 2%. The study aimed to evaluate the influence of these fibers on the engineering properties of the soil. The results indicated that the formation of cementitious compounds such as calcium silicate hydrate (CSH) and calcium aluminate hydrate (CAH) reduced swelling behaviour. The optimum performance was observed with the addition of 1% CF and 1.5% PPF, which showed significant improvement in soil properties. In a laboratory study on *in situ* chemical soil stabilization, Rao *et al.* (2003) reported that strong reactions between soil and lime reduced soil plasticity, minimized swelling, and enhanced the unconfined compressive strength of lime-slurry-treated specimens. This research aims to enhance the stability of expansive soil by incorporating lime, fly ash, and silica fume at varying percentages (2%, 4%, and 6%). The focus is on mitigating free swelling and swell pressure in the soil. The methodology employed in this paper introduces a practical approach for utilizing lime, fly ash, and silica fume as additives to improve soil properties. Consequently, the proposed technique for applying a stabilizer can be regarded as an innovative approach to soil stabilization.

2. MATERIALS AND METHODS

2.1 Bentonite Nanoclay

Bentonite Nanoclay (BNC) is a natural and versatile material that has many uses. It has a special property of swelling and becoming sticky when it absorbs water. It is mainly made of montmorillonite, which is a type of clay mineral that can swell (Fig. 1). It is useful for many industries because of its swelling and sticky properties. The geotechnical properties of the BNC are mentioned in Table 1.



Fig. 1: Bentonite nanoclay

Table 1. Properties of bentonite nanoclay

S. No	Properties	Value
1	Specific gravity	2.56
2	Liquid limit (%)	129
3	Plastic limit (%)	75
4	Plasticity index	54
5	Differential free swell index (%)	129
6	Maximum dry density (g/cc)	1.470
7	Optimum moisture content (%)	32

2.2 Lime

Lime is a useful chemical compound that is abundant in calcium oxide (CaO) or calcium hydroxide ($Ca(OH)_2$) and comes from limestone or other materials that have a lot of calcium. Lime has been used for a long time in construction as an important part of mortar and plaster because it helps them stick together (Fig. 2).

2.3 Fly Ash

Fly ash is a thermal by-product of the power plant, and it is a greener alternative in the construction industry, and it is a valuable material for sustainable construction activities (Fig. 3). It reacts with calcium hydroxide and forms solid bonds that last long. Nowadays, it is widely used in the construction sector for concrete, brick, and pavement manufacturing. It also costs very low compared to other materials.



Fig. 2: Lime



Fig. 3: Fly Ash

2.4 Silica Fume

Silica fume is a waste material that comes from making silicon metal and ferrosilicon (Fig. 4). It is mostly made of very fine particles of silica that have no shape and are very pure, with 85-98% of them being silicon dioxide (SiO_2). Moreover, its use can help reduce the amount of carbon emissions in construction projects as it partially replaces cement, making it an environmentally friendly material in various industries.

3. TESTS PERFORMED

Most of the earlier research works used the admixture from 0.5% to 2% for stabilization of clay. Hence, in the present work, BNC with 2%, 4%, and 6%

lime, fly ash, and silica fume were used to investigate the moisture-density relations and stress-strain analysis. The swelling index and Atterberg's limits were determined in the tests. The plasticity characteristics of clay soil beyond 6% addition of admixtures have a scope for further intensive research.



Fig. 4: Silica fume

3.1 Standard Proctor Test

Soil compaction involves the elimination of void spaces within the soil to increase its density. The dry density of the soil is utilized as a measure of the effectiveness of this compaction process. When water content and dry density data are graphed, it yields a curve known as the compaction curve that identifies the optimal water content and maximum dry density. Initially weigh the mould with the base plate. A 3-kg soil sample was taken, and an initial water content of approximately 23% was introduced, as shown in Fig. 5 and Fig. 6. The soil sample was thoroughly mixed with water to ensure uniform moisture distribution. The prepared sample was then compacted in three layers, with 25 blows applied uniformly to each layer, as illustrated in Fig. 7.



Fig. 5: Clay with stabilizer



Fig. 6: Addition of water to the sample



Fig. 7: Compaction

The mould containing the compacted soil was weighed, and the corresponding dry density was calculated. The test was repeated by increasing the water content in increments of 3% for each trial until a reduction in the weight of the soil sample was observed. Initially, the mould along with the base plate was weighed with an accuracy of 1 g. A soil sample of approximately 3–4 kg was collected. For clayey soil, water was added to achieve an initial moisture content of about 23% for the first trial. For subsequent trials, the water content was increased by 3% in each test. The measured values of water content and dry density were plotted, and the Optimum Moisture Content (OMC) and

Maximum Dry Density (MDD) were determined from the compaction curve.

The interaction between lime and clay minerals, particularly montmorillonite found in bentonite, results in the creation of stable calcium silicate hydrates and calcium aluminate hydrates. This chemical reaction is instrumental in diminishing the plasticity of the soil and enhancing its strength and durability. The outcome of this process is the development of stable compounds, namely calcium silicate hydrates and calcium aluminate hydrates, which play a pivotal role in soil stabilization. This reaction effectively reduces the plasticity of the soil, contributing to improved strength and overall durability of the soil matrix. When BNC was treated with lime at 2%, 4%, and 6%, the dry density of the sample increased by 2.99%, 2.85%, and 2.58%, respectively. This demonstrates how the compaction property increases with increasing lime content (Fig. 8).

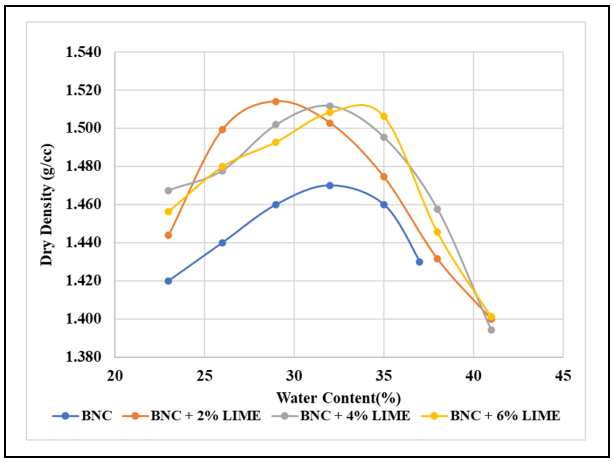


Fig. 8: Compaction curve for BNC with lime

The pozzolanic reaction is a fundamental process, often observed when fly ash interacts with calcium hydroxide, which is usually found in the soil or produced during hydration reactions (Raja *et al.* 2024). As a result of this interaction, additional cementitious compounds are formed, thereby playing a significant role in the stabilization of the soil. A byproduct of this reaction is the creation of calcium silicate hydrate (C-S-H) gel, contributing to increased strength and diminished plasticity within the soil matrix. When BNC was treated with fly ash at 2%, 4%, and 6%, the dry density of the sample increased by 2.1%, 2.51%, and 5.71%, respectively. This shows the increase in fly ash content increases the compaction property as illustrated in Fig. 9.

Silica fume, known for its high reactivity as a pozzolan, can induce alterations in the properties of soil when incorporated with BNC. The key mechanism governing soil stabilization with silica fume was the pozzolanic reaction. In this process, silica fume reacted with calcium hydroxide present in the soil or produced during chemical reactions, leading to the formation of calcium silicate hydrate (C–S–H) gel. This reaction significantly altered the soil structure and contributed to improved stabilization. When untreated BNC was treated with silica fume at 2%, 4%, and 6%, the dry density increased by 4.62%, 4.42%, and 3.6%, respectively. This shows the increase in silica fume content decrease in the compaction property (Fig. 10).

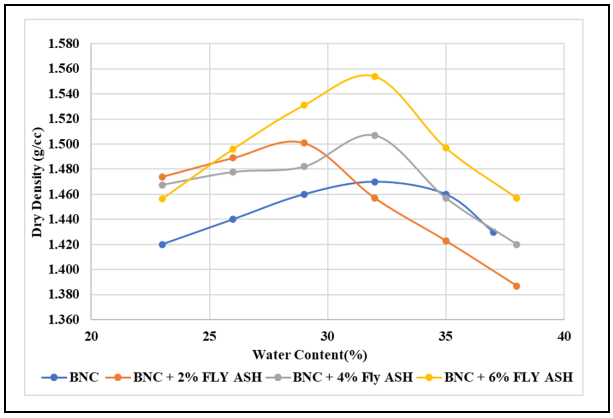


Fig. 9: Compaction curve for nano BNC with fly ash

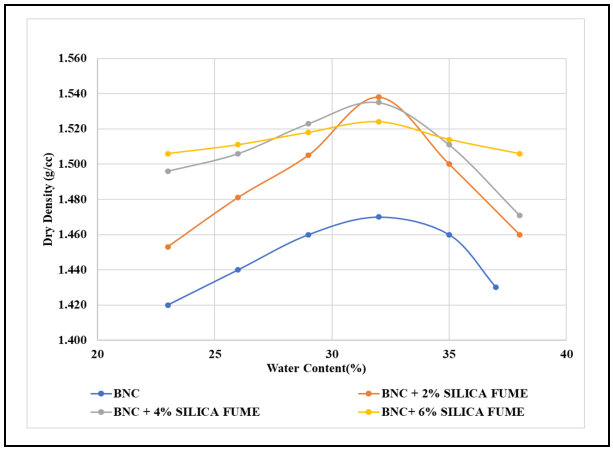


Fig. 10: Compaction curve for BNC with silica fume

3.2 Unconfined Compression Strength Test

The unconfined compression strength is determined as per the norms specified by IS 2720 (Part 10). The test was carried out with the sample which is compacted from the procedure mentioned in clause 3.1. The sampling of the wet soil was done using the cylindrical tube (Fig. 11). Then, the wet cylindrical sample was pushed out from the cylindrical tube by using an ejector with negligible disturbance (Fig. 12).

The initial length, diameter, and weight of the specimen were measured, and the sample was kept under the bottom plate of the unconfined compression strength loading machine. The reading of load (in kN) and deformation (in mm) were noted at steady intervals. The test was continued until failure occurred or until an axial strain of 20% was reached, as specified in Clause 6.3 of

IS 2720 (Part 10). The failure pattern of the test specimen was observed and recorded (Fig. 13).



Fig. 11: Sample in the cylindrical tube



Fig. 12: Extraction of sample



Fig. 13: Failure pattern of the specimen

The unconfined compression test serves as a method for evaluating the strength properties of soil when subjected to axial loading conditions. The outcomes of this test play a crucial role in assessing the efficacy of soil stabilization treatments. In the context of lime interacting with clay minerals, particularly montmorillonite within bentonite, the chemical process involved is identified as the pozzolanic reaction. This reaction is integral to the alteration of the soil's properties, contributing to its stabilization. In this test untreated BNC was treated with lime at 2%, 4%, and 6%. The results showed an increase of 34% and 36.65% at 2% and 6% lime content, respectively, while a slight decrease to 45.9% was observed at 4% lime content (Fig. 14).

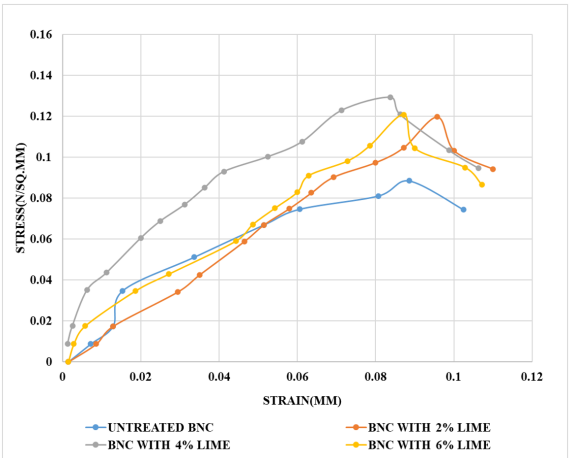


Fig. 14: Stress-strain curve for BNC with Lime

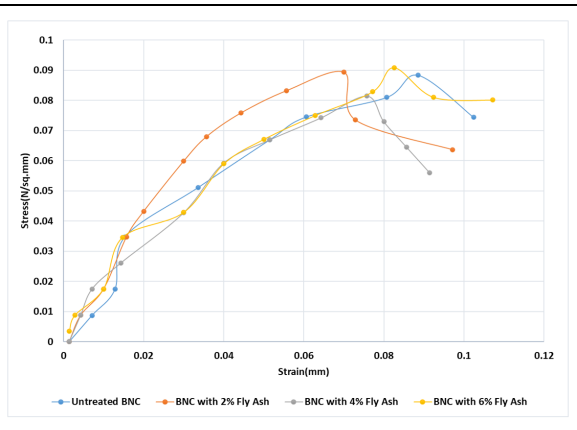


Fig. 15: Stress-strain curve for BNC with fly ash

The interaction between BNC and fly ash is complex and depends on several factors, including material composition. A key mechanism involved is the pozzolanic reaction, in which fly ash reacts with calcium hydroxide to form cementitious compounds that influence the overall properties of the mixture. When untreated BNC was treated with fly ash at 2%, 4%, and 6%, the dry density showed a continuous increase of 1.01%, 1.80%, and 2.81%, respectively (Fig. 15).

Silica fume reacts with calcium hydroxide to form calcium silicate hydrate (C–S–H) gel, which

contributes to soil densification and improved stabilization. When untreated BNC was treated with silica fume at 2%, 4%, and 6%, the dry density showed a continuous increase of 36%, 44%, and 58.9%, respectively (Fig. 16).

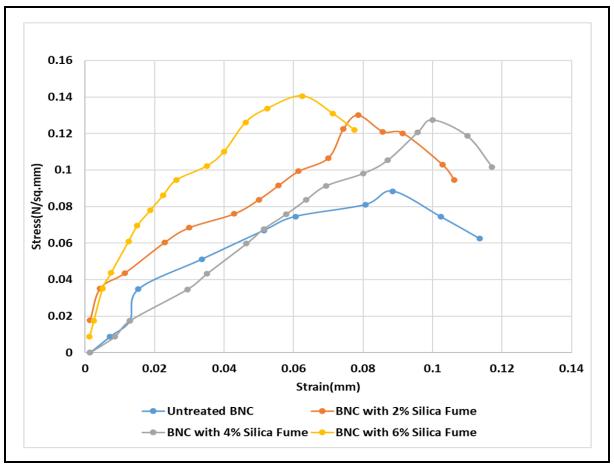


Fig. 16: Stress-strain curve for BNC with silica fume

4. CONCLUSION

The interaction of bentonite nanoclay (BNC) with lime, fly ash, and silica fume significantly influences soil stabilization. Lime induces pozzolanic reactions forming calcium silicate hydrates (C–S–H) and calcium aluminate hydrates (C–A–H), resulting in reduced plasticity, improved strength, and better compaction. Similarly, fly ash reacts with BNC to form cementitious compounds, enhancing compressive strength, load-bearing capacity, and reducing plasticity. Silica fume also promotes strong pozzolanic reactions, leading to further improvements in strength and stability. Among all additives, silica fume treatment with untreated BNC showed the highest performance, with maximum increases in dry density (4.62%) and compressive strength (58.09%). This indicates that silica fume is the most effective stabilizer for expansive clay.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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REFERENCES

Abdila, S. R., Abdullah, M. M. A. B., Ahmad, R., Burduhos Nergis, D. D., Rahim, S. Z. A., Omar, M. F., Sandu, A. V., Vizureanu, P. and Syafwandi, Potential of Soil Stabilization Using Ground Granulated Blast Furnace Slag (GGBFS) and Fly Ash via Geopolymerization Method: A Review, *Mater.(Basel),* 15(1), 375 (2022). https://doi.org/10.3390/ma15010375

Al-Gharbawi, A. S. A., Najemalden, A. M. and Fattah, M. Y., Expansive Soil Stabilization with Lime, Cement, and Silica Fume, *Appl. Sci.,* 13(1), 436 (2022). https://doi.org/10.3390/app13010436

Alrubaye, A. J., Hasan, M. and Fattah, M. Y., Stabilization of soft kaolin clay with silica fume and lime, *Int. J. Geotech. Eng.,* 11(1), 90–96 (2017). https://doi.org/10.1080/19386362.2016.1187884

Anand, D., Sharma, R. K. and Sharma, A., Improving Swelling and Strength Behavior of Black Cotton Soil Using Lime and Quarry Dust, 601–609 (2021). https://doi.org/10.1007/978-981-15-9554-7_54

Deepak, M. S., Rohini, S., Harini, B. S. and Ananthi, G. B. G., Influence of fly-ash on the engineering characteristics of stabilised clay soil, *Mater. Today Proc.,* 37, 2014–2018 (2021). https://doi.org/10.1016/j.matpr.2020.07.497

Dharini, V., Balamaheswari, M. and Nevis Presentia, A., Enhancing the strength of expansive clayey soil using lime as soil stabilizing agent along with sodium silicate as grouting chemical, *Mater Today Proc.*, (2023). https://doi.org/10.1016/j.matpr.2023.05.156

Hasan, M., Zaini, M. S. I., Yie, L. S., Masri, K. A., Putra Jaya, R., Hyodo, M. and Winter, M. J., Effect of optimum utilization of silica fume and eggshell ash to the engineering properties of expansive soil, *J. Mater. Res. Technol.,* 14, 1401–1418 (2021). https://doi.org/10.1016/j.jmrt.2021.07.023

Mir, B. A. and Sridharan, A., Physical and Compaction Behaviour of Clay Soil–Fly Ash Mixtures, *Geotech. Geol. Eng.,* 31(4), 1059–1072 (2013). https://doi.org/10.1007/s10706-013-9632-8

Phanikumar, B. R., M, J. R., E, R. R., Silica fume stabilization of an expansive clay subgrade and the effect of silica fume-stabilised soil cushion on its CBR, *Geomech. Geoengin.,* 15(1), 64–77 (2020). https://doi.org/10.1080/17486025.2019.1620348

Raja, K., Sampathkumar, V., Anandaraj, S., Hariswaran, S., Amarapathi, G. D., Srisaran, B., Comparative Study on Stabilisation of Bentonite Clay Using Municipal Incinerated Bottom Ash and Fly Ash, In: Reddy, K.R., Ravichandran, P.T., *Lect. Notes Civ. Eng.*, 398, 359–368 (2024). https://doi.org/10.1007/978-981-99-6229-7_30

Raja, K., Venkatachalam, S., Vishnuvardhan, K., Siva Rama Krishnan, R., Tamil Selvan, V. and Vetriselvan, N., A review on soil stabilization using rice husk ash and lime sludge, *Mater. Today Proc.,* 65, 1205–1212 (2022). https://doi.org/10.1016/j.matpr.2022.04.178

Ramezani, S. J., Toufigh, M. M. and Toufigh, V., Utilization of Glass Powder and Silica Fume in Sugarcane Bagasse Ash-Based Geopolymer for Soil Stabilization, *J. Mater. Civ., Eng.* https://doi.org/10.1061/(ASCE)MT.1943-5533.0004704

Rao, S. M. and Thyagaraj, T., Lime slurry stabilisation of an expansive soil, *Proc. Inst. Civ. Eng. - Geotech. Eng.,* 156(3), 139–146 (2003). https://doi.org/10.1680/geng.2003.156.3.139

Saygili, A. and Dayan, M., Freeze-thaw behavior of lime stabilized clay reinforced with silica fume and synthetic fibers, *Cold Reg. Sci. Technol.,* 161, 107–114 (2019). https://doi.org/10.1016/j.coldregions.2019.03.010

Seyrek, E., Engineering behavior of clay soils stabilized with class C and class F fly ashes, *Sci. Eng. Compos. Mater.,* 25(2), 273–287 (2018). https://doi.org/10.1515/secm-2016-0084

Sharma, R. K., Utilization of Fly Ash and Waste Ceramic in Improving Characteristics of Clayey Soil: A Laboratory Study, *Geotech. Geol. Eng.,* 38(5), 5327–5340 (2020). https://doi.org/10.1007/s10706-020-01366-7

Shenal Jayawardane, V., Anggraini, V., Emmanuel, E., Yong, L. L. and Mirzababaei, M., Expansive and Compressibility Behavior of Lime Stabilized Fiber-Reinforced Marine Clay, *J. Mater. Civ. Eng.*, https://doi.org/10.1061/(ASCE)MT.1943-5533.0003430

Singh, P., Kumar Dash, H. and Samantaray, S., Effect of silica fume on engineering properties of expansive soil, *Mater. Today Proc.,* 33, 5035–5040 (2020). https://doi.org/10.1016/j.matpr.2020.02.839

Syed, M., GuhaRay, A. and Garg, A., Performance Evaluation of Lime, Cement and Alkali-Activated Binder in Fiber-Reinforced Expansive Subgrade Soil: A Comparative Study, *J. Test. Eval.,* 50(6), 3054–3077 (2022). https://doi.org/10.1520/JTE20210054

Taki, K. and Bhattacharya, P., Comparative Study of Expansive and Non-expansive Soils Stabilized with Lime and Rice Husk Ash (RHA), 553–563 (2020). https://doi.org/10.1007/978-981-15-0886-8_45

Tiwari, N. and Satyam, N., Experimental Study on the Influence of Polypropylene Fiber on the Swelling Pressure Expansion Attributes of Silica Fume Stabilized Clayey Soil, *Geosci.,* 9(9), 377 (2019). https://doi.org/10.3390/geosciences9090377

Zorluer, I. and Gucek, S., The effects of marble dust and fly ash on clay soil, *secm,* 21(1), 59–67 (2014). https://doi.org/10.1515/secm-2012-0100