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 are 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 and bumping of roads, 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. It can be sought out by research paper we can consider lime as one of our 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 chemical with hydrated lime powder as a stabilizer. Also, this research concluded that the CBR value is multiplied many times than the untreated soil while using an optimal mix of the lime & sodium silicate (Dharini *et al.* 2023). The experiment discussed the optimal percentage of RHA and lime sludge to use for stabilization purposes (Raja *et al.* 2022). 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 had been used separately and with lime. It shows that increase in UCS (Anand *et al.* 2021). The use of geopolymer for the binding purpose is studied briefly along with industrial wastes such as Fly Ash and GGBFS. Fly Ash and GGBFS are used as a stabilization agent (Abdila *et al.* 2022). The two different Fly Ash were used with lime to study the plasticity & workability of clayey soil. It concludes that the soil is 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 is treated with Fly Ash of varying percentages. The samples were dried for 28 & 90 days and the strength was analyzed. The quality of clay is enhanced by the addition of marble dust and Fly Ash, which are known to stabilize and strengthen the soil. It experimented with the different qualities of marble dust and Fly Ash and found that the mixture got better from time to time. It proved that the environmentally friendly way of stabilization (Zorluer *et al.* 2014). The experiment 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 (Mir *et al.* 2013). 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 is experimented with and proved the cost an efficient way of stabilization. The results show that the combo of FA & ceramic wastes is better rather than Fly Ash and ceramic wastes alone (Sharma, 2020).

The study of using sugarcane and baggase ash in untreated expansive soils shows the improved chances of geopolymer gel production. It also studies the toxicity character of using SCBA for environmental considerations. 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 is done using SF & ESA of various percentages. It shows the reduction of specific gravity, plasticity, and dry density. The shear strength is also improved significantly than untreated soil (Hasan *et al.* 2021). The swelling pressure is decreased when soil is treated with silica fume from 0 to 10%. It also reports the increase in OMC & decreases in MDD while adding silica fumes. It additionally increases cohesion which is the reason for its strength (Singh *et al.* 2020). The inclusion of polypropylene fiber along with silica fume discusses the mechanic-chemical stabilization of providing clayey soil (Tiwari *et al.* 2019). The enhancement of clayey soil is done with varying lime content consisting of 4% silica fume content discusses the pozzolanic reaction between soil – lime & soil – silica fume mixes (Alrubaye *et al.* 2017). The mixtures of silica fume, fiber, and lime with expansive soils of 28 days, increases the mechanical properties such as UCS, evaluate the reduction of freeze (Saygili *et al.* 2019). The BNC with limestone and hydrated lime ranged from 0 to 10 %. The results show that the swell pressure and swelling potential were reduced. The swell potential decreases from 34.5 to about 26.5 % and 1 % in the case of clay samples mixed with 10 % limestone and 10 % hydrated lime, respectively. The limestone reduces the strength of the clay. When treated with hydrated lime, it increases the strength of the clay. The addition of lime and Fly Ash significantly impacts soil behavior. Lime tends to reduce the FSI by improving workability and reducing plasticity. Meanwhile, Fly Ash enhances pozzolanic reactivity, affecting swelling potential, swelling pressure, and other engineering characteristics. Swell pressure and Swell potential were reduced when Fly Ash was added. It further reports that the Compaction and UCC values were improved at 4 % Lime and reduced at 6% Lime Content (Phanikumar *et al.* 2020). The clay with Lime, Cement, and alkali-activated binder with the reinforcement of PF, glass, hemp, and CF. The strength performance of AAB is better than Lime and cement binders by 35 to 40%. This study also finds the slag and Fly Ash contents are responsible for volumetric instability and tensile cracks of clay soil (Syed *et al.* 2022).

Taki *et al.* (2020) compared the soils treated with Lime and RHA. The UCC values were acquired after 0, 3, 7, 21, and 28 of watering. RHA reduces strength because of the presence of coarser constituents. The UCS values are 3 folds better than the RHA-treated clay. The shear strength was decreased when the stabilizers were used beyond the optimum dosages. The usage of Fly Ash at 10, 20, 40, 60, 80 percent. It shows that swell potential is reduced by 40%. Fly Ashes alter the strength of BC soil significantly by pozzolanic reactions that increase the strength. For Fly Ashes with higher reactivity, the effect of pozzolanic reactions overrides the effect of silty behavior and vice versa for reactive Fly Ash. Shenal Jayawardane *et al.* (2020), added lime and fiber in Marine clay to study the expansive and compressibility of the impact of adding coir CF and PPF to the soil. Different percentages (0.5%, 1%, 1.5%, and 2%) of these fibers were considered. The research aimed to understand how these fibers affect soil properties. Due to the formation of CSH and CAH the swelling in a laboratory study on in-situ chemical soil stabilization, the addition of 1% CF or 1.5% PPF led to positive effects. The strong reactions between soil and lime reduced soil plasticity minimized swelling, and enhanced the unconfined compressive strength of lime-slurry-treated specimens (Rao *et al.* 2003). 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

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). BNC 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).

Fig. 2: Lime

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. 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.

Fig. 4: Silica fume

3. TESTS PERFORMED

Most research was performed by adding admixture from 0.5% to 2% for stabilization of clay. Hence to enhance the research value BNC with 2%, 4%, and 6% Lime, Fly Ash, and Silica Fume are 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.

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. Take 3 kilograms of sample and introduce water content of about 23% represented in (Fig. 5 and Fig. 6) at an initial trial. Mix the soil sample thoroughly with water and compact it into 3 layers and 25 blows evenly for each layer (Fig. 7).

Fig. 5: Clay with stabilizer

Fig. 6: Addition of water to the sample

Fig. 7: Compaction

Weigh the mould containing the soil and use this to calculate the dry density. Repeat the tests by increasing the water content by 3% until the weight of the soil sample is reduced perform this test, please adhere to the following steps: Begin by weighing the Mold along with the base plate with a precision of 1 gram. Gather a soil sample weighing approximately 3-4 kilograms. If the soil exhibits clayey characteristics, introduce water to attain an initial water content of about 23% for the first test. For subsequent tests, increment the water content by 3% in each trial. Plot the water content and dry density values on a graph and determine the Optimum Moisture Content (OMC) and Maximum Dry Density (MDD) from the resulting 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 is treated with lime with 2%, 4%, and 6% the dry density of the sample is 2.99%, 2.85%, and 2.58% increased respectively. This demonstrates how the compaction property increases with increasing lime content (Fig. 8).

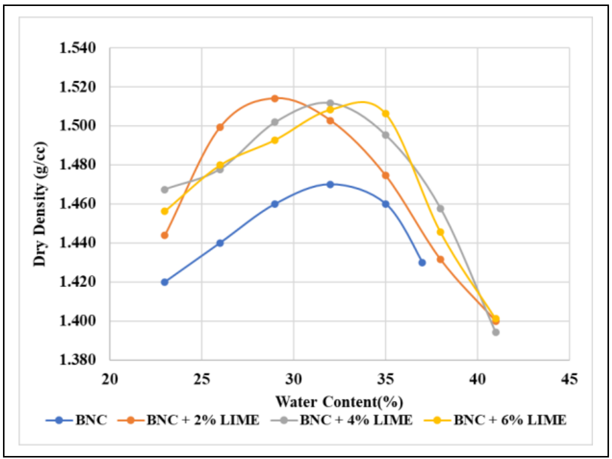

Fig. 8: Compaction curve for BNC with Lime

The pozzolanic reaction is a fundamental process, often observed when Fly Ash interacts with calcium hydroxide ($Ca(OH)_2$), 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 heightened strength and diminished plasticity within the soil matrix. When BNC is treated with Fly Ash with 2%, 4%, and 6% the dry density of the sample is 2.1%, 2.51%, and 5.71% increased respectively. This shows the increase in Fly Ash content increases the compaction property as illustrated (Fig. 9).

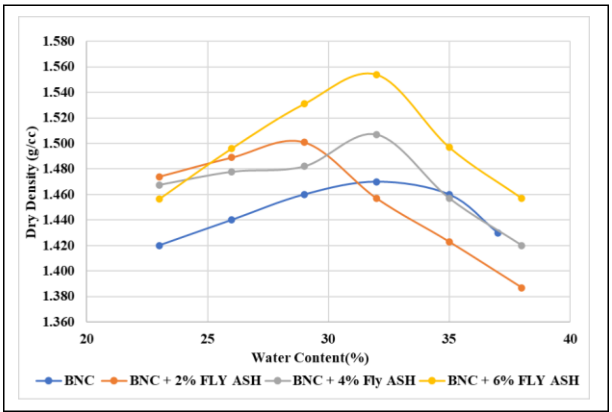

Fig. 9: Compaction curve for nano BNC with Fly Ash

Silica fume, known for its high reactivity as a pozzolan, can induce alterations in the properties of soil when incorporated with BNC. The key reaction associated with silica fumes in soil stabilization is the pozzolanic reaction. In this process, silica fume engages with calcium hydroxide ($Ca(OH)_2$), potentially already existing in the soil or generated through other reactions, leading to the formation of calcium silicate hydrate (C-S-H) gel. This chemical transformation is instrumental in modifying the soil's characteristics and contributing to its stabilization. When untreated BNC is treated with silica fume with 2%, 4%, and 6% the dry density of the sample is 4.62%, 4.42%, and 3.6% increases respectively. This shows the increase in silica fume content decrease in the compaction property (Fig. 10).

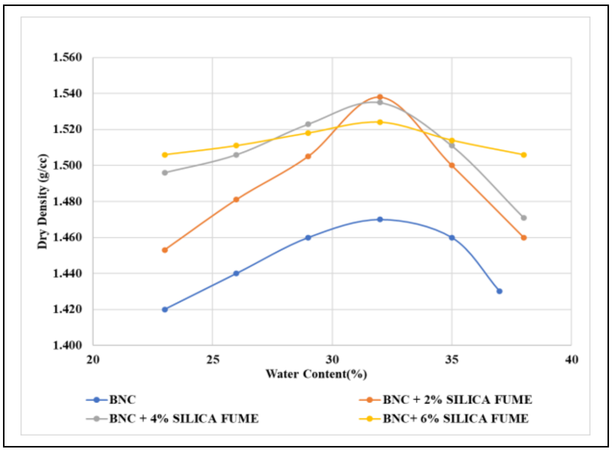

Fig. 10: Compaction curve for BNC with Silica fume

Fig. 11: Sample in the cylindrical tube

Fig. 12: Extraction of sample

3.2 Unconfined Compression Strength Test

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

The diameter to length should be in the range of 2-2.5. The initial length, diameter, and weight of the specimen are measured, and the sample is kept under the bottom plate of the unconfined compression strength loading machine. The reading of load (in kN) and deformation (in mm) are noted at steady intervals. The test should last until the failure occurs or it occurs 20% of axial strain as mentioned in Clause 6.3 of IS 2720 (Part 10). The failure pattern of the test specimen shall be noted, if possible (Fig. 13).

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 is treated with lime of 2%, 6% it results in increases of 34% and 36.65%, and 4% of lime results in a slight decrease of 45.9% (Fig. 14).

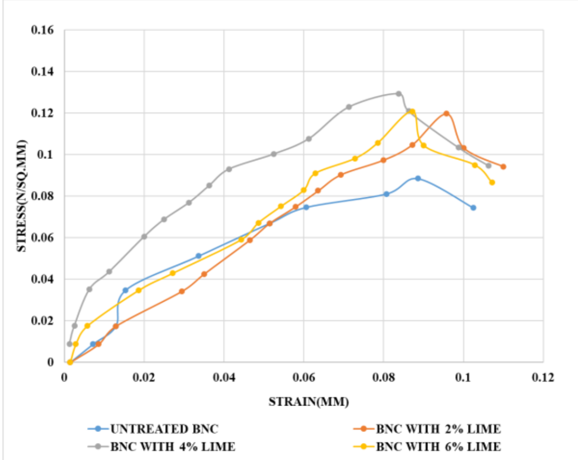

Fig. 14: Stress-strain curve for BNC with Lime

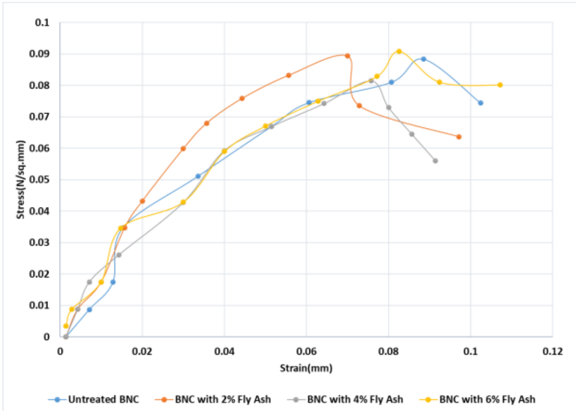

Fig. 15: Stress-strain curve for BNC with Fly Ash

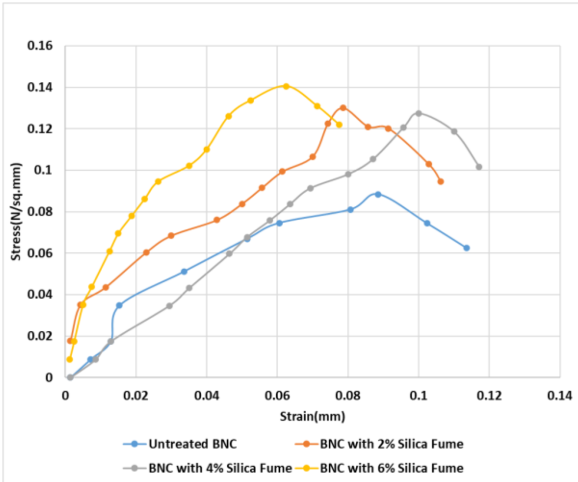

Fig. 16: Stress-strain curve for BNC with Silica fume

The interactions between BNC and Fly Ash can exhibit complexity, contingent upon several factors such as material composition. Nonetheless, a pivotal reaction in this context is the pozzolanic reaction, characterized by the interaction of Fly Ash with calcium hydroxide ($Ca(OH)_2$). This reaction leads to the creation of cementitious compounds, influencing the overall properties of the mixture. Treatment of Fly Ash with untreated BNC of 2%, 4%, 6% it results in continuous increases dry density as 1.01%, 1.80% and 2.81% (Fig. 15).

Silica fume reacting with calcium hydroxide ($Ca(OH)_2$) to form calcium silicate hydrate (C-S-H) gel. The silica fume treated with the untreated BNC with a mix of 2%, 4%, and 6% results in a continuous increase in dry density at 36%, 44%, and 58.9% (Fig. 16).

4. CONCLUSION

The interactions between BNC and lime, Fly Ash, and silica fume hold significant implications for soil stabilization and construction applications. The addition of lime induces pozzolanic reactions, resulting in the formation of stable calcium silicate hydrates and calcium aluminate hydrates. This leads to reduced plasticity, improved strength, and enhanced compaction characteristics, making it a viable method for soil stabilization. Similarly, the combination of BNC with Fly Ash triggers pozzolanic reactions, forming cementitious compounds that contribute to increased compressive strength, improved load-bearing capacity, and reduced plasticity. Additionally, when BNC reacts with silica fume, the ensuing pozzolanic reactions result in heightened compressive strength, improved load-bearing capacity, and decreased plasticity. As a result, silica fume reacts with untreated BNC which has an MDD of 4.62 % and the compressive strength of 58.09% is the maximum obtained by any other material blended with BNC. These results suggest that silica fume stabilization is an effective method for treating expansive clay.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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