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Original Article

Effect of High-Volume Class F Fly Ash and Nano Lime on the Swelling Behavior and Microstructure of Expansive Soil

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Abstract *- A balance between stabilization of expansive soil and taking care of sustainability issues has been a major challenge. The Indian environmental challenge is the large quantities of ash produced by thermal power plants, which are being disposed of. Using this fly ash as a stabilizer material is an environmentally friendly choice, which minimizes traditional soil replacement and economic construction. Over the past years, nanomaterials have presented a great potential in soil stabilization. This research paper examines the compound application of class F fly ash and nano lime in enhancing expansive clay located in Rajkot city. A synthesis of nano lime was done using a thermal decomposition procedure, and fly ash was obtained commercially. The fly ash was replaced with soil samples at a rate of 40%, 60%, and 80% by dry weight, and nano lime was added to the soil at 0.5% and 1.0% by dry weight. Geotechnical tests like Atterberg limits, Free Swell index and Swell pressure were performed, and microstructural analysis was carried out. The findings reveal that the swelling behavior of expansive soil significantly improves with increased dosages of fly ash and nano lime used in combination. The most effective performance was achieved with a mixture of 80% fly ash and 1% nano lime, leading to substantial reductions in plasticity and swell pressure and a marked improvement in shrinkage resistance. This combined stabilization strategy offers a sustainable and locally suitable solution for managing problematic soils in regions like Rajkot.*

Keywords *- Expansive soil stabilization, High Volume Fly ash, Nano lime, Atterberg limits, Swell pressure, Microstructure Analysis.*

1. Introduction

The expansive soil, also called shrink-swell soil, has large volume changes that depend on the change in moisture content. This type of soil is made mainly of clay minerals, swells when absorbed with water, and shrinks when it dries up. Stabilizing these soils is essential since engineers have limited alternatives for replacing damaged soils due to sustainability and environmental issues [1, 2]. For instance, the basaltic rock formation (Black soil) is the second most common soil type in Rajkot, India, with over 20% of the soil coated with montmorillonite minerals. When the moisture level of this mineral varies, it has a huge potential for volumetric variations [3]. Because of this characteristic, buildings built on this kind of soil sometimes experience significant settlements that lead to fractures, which can compromise their serviceability and occasionally even their safety [4]. Handling difficult soils can be greatly enhanced by utilizing industrial waste materials that possess cementitious properties [5]. Other investigators have attempted to enhance the soils using waste products, e.g., micro-fine slag, red mud, plastic, and ceramics. Because pulverized coal can be burned and can be utilized to generate fly ash, which is often used to generate electricity, most researchers of the last several decades have used fly ash in other applications [6]. Coal-fired thermal power plants are prevalent throughout the nation as a result of rising electricity demand and the availability of sufficient coal reserves [7]. Fly ash in huge amounts has been produced by the 30-45% ash concentration of Indian coal [8]. In addition to requiring vast tracts of land for disposal, leftover fly ash pollutes the air and water. In the first half of 2021–2022, around 133 million tons of fly ash were created; 24 million tons of that fly ash went unused, according to the Central Electrical Authority (CEA) in New Delhi.

According to the available data, fly ash was utilized in approximately 32% of the ways that cement was made, 13% of fly ash-based building products, 15% of land reclamation, 6% of mine filling, etc., 21% of road and embankment construction, and only 0.04% of wasteland development [9]. The fly ash can be used a lot in the wasteland development. Fine-grained dust is called fly ash. Mostly made up of silica, alumina, and several oxides and alkalis [10]. Fly ash's impact on the strength of the soil. Numerous variables affect expansive soil, including the kind of fly ash and its particle size. Fly ash in the ideal quantity is 10–40% to reduce the possibility of swell [11]. The addition of lime-fly ash to the black cotton soil to change its engineering properties. Considering that the void ratio becomes larger when the soil is mixed with lime and fly ash, the mixture between fly ash and soil becomes more permeable [12]. Because free lime cementation occurs with longer cure times, permeability reduces.

Furthermore, during a month-long curing period, 50%–60% more unconfined compression strength is achieved. In order to achieve the 20% reduction in the liquid limit, you can add 10–12% lime or 50–60% fly ash [13]. Similarly, a combination of lime and fly ash in stabilizing expansive soil in the sub-base; a combination of lime and fly ash in ratio of 1:4 would be able to multiply the CBR and UCS and save 28 percent in terms of constructing the pavement to make it a sustainable and a cost-effective alternative to developing the road infrastructure in that area [1]. As a result, the soil is easier to work with, and additional moisture may be added before adding fly ash and lime to get the right density.

Notwithstanding fly ash's cementing abilities, investigations indicate that fly ash by itself cannot sufficiently enhance geotechnical qualities to be used in pavement and foundation design. However, fly ash has been found to be useful in the literature, particularly when paired with other chemicals [14, 15]. In this aspect, Kashimiazar et al. [16] explore how nano-silica enhances the behavior of lime-treated marl soil, focusing on strength, permeability, and durability. Results reveal that nano-silica significantly refines the soil's structure and boosts resistance to moisture and deformation, making it a smart addition for sustainable ground improvement. While discussing about the role of lime in soil, Harianja et al. [17] investigate how lime particles of different sizes affect the stabilization of expansive soils. By comparing their impact on strength, plasticity, compaction, and bearing capacity, the research shows nano-lime delivers the most significant improvement in soil properties, offering a promising route for efficient, durable ground treatment.

Many researchers also aimed to use eco-friendly materials [18] for stabilization of expansive soils. Bekkouche [18] and Majid [19] investigated the impact of natural fibers on expansive soils, finding that the mechanical behavior of the soil was considerably changed by the fibers. Also, a significant reduction in swell potential and plasticity, proving that plant fibers offer a sustainable and cost-effective method for enhancing soil stability. In order to enhance the compressive strength of cement mortar, Alharbi & Abadel [20] added glass waste nanoparticles and a large portion of fly ash. Mocharla et al. [21] proposed large quantities of slag sand and fly ash concrete mixes, evaluating various attributes such as water penetration, temperature sensitivity, and strength. Liu et al. [22] researched the mechanical strength under sulphate attack, the physical properties of self-compacting concrete, and deterioration processes. Kelechi et al. [23] enhanced the self-compacting rubber concrete qualities in terms of the incorporation of calcium carbide waste and the addition of several additives. Finally, Amran et al. [24] explored the characteristics and structure of green concrete reinforced with high fly ash contents, compared their sustainability in terms of environmental concerns, and implemented several methods of analysis.

Improving expansive soil by using high-volume fly ash leads to high engineering quality and a reduced environmental effect [21]. Yet, there are a few disadvantages to this strategy. Because of the high expense of large-scale materials, some projects cannot use them. This presents one big challenge. The impacts of nano lime and high-volume fly ash on soil properties may not be stable or reliable. The performance and long-term life of the changed soil can change depending on the soil's character and the conditions, making its results unpredictable.

There is a lack of studies on combining the high-volume Class F fly ash with nano lime, particularly their use in synergistic terms of the effects on swelling behavior and microstructural properties. Moreover, no related studies in the current literature refer to a complete microstructural analysis that refers to geotechnical enhancements. The present research centers on these major deficits by examining the compound influence of nano lime and high-volume fly ash on geotechnical and microstructural properties of expansive soil.

2. Materials and Methodology

2.1. Materials

Out of the raw materials, fly ash, nano lime and black cotton soil from Rajkot were the main ingredients chosen. Since black cotton soil is a widespread kind of soil in the area, the study began by examining it. To improve the soil's engineering properties, fly ash, which is formed when coal is burned, was added thanks to its pozzolanic qualities. For this study, the dark grey Class F fly ash was obtained from Suyog suppliers who worked at a thermal power station in Wanakbori. Nano lime was prepared in the lab and added to improve the soil's mechanical qualities and suitability for construction. These carefully chosen materials were used to explore potential synergistic impacts on geotechnical performance and soil improvement.

Expansive clay was sampled from a site in Rajkot City, Gujarat, in India. It was at a depth between 1 and 2 meters that expansive clay was discovered. The entire disturbed soil was meticulously excavated, placed in plastic bags and taken to the lab where it could be further analysed as per the Indian Standard. Information about this soil, including its density, optimal moisture content, plasticity and categorization, is given in Table 1.

Table 1. Expansive soil of rajkot index and engineering properties

Sr. No.	Property	Value
1	Specific gravity	2.41
2	Average soil pH	8.25
3	Liquid limit (%)	80
4	Plastic limit (%)	34
5	Shrinkage limit (%)	9
6	Free Swell Index (%)	70
7	Soil classification	CH
8	Optimum water content (%)	24
9	Maximum dry density (g/cm^3)	1.48
10	Unconfined Compressive Strength (kN/m^2)	60

2.1.1. Nano Lime Preparation

The synthesis of the Nano lime in the study is carried out at Marwadi University at the Nano-science Laboratory of the Department of Physics, based on the bottom-up strategy relying on the wet chemical method.

Fig. 1 Preparation of nano lime using the Sol-gel technique

For this wet chemical approach, the sol-gel technique shown in Figure 1 works well for manufacturing nano lime materials. In order to achieve fine gelation of the solution, the precursor $Ca(NO_3)_2$ has been treated in accordance with D. Dhruv et al. [25]. Fine particles of nano lime were obtained by drying it at a temperature of 700ºC after gelation. The produced nano lime was examined and analyzed using X-Ray Diffraction (XRD) scan and Field Emission Scanning Electron Microscopy (FESEM) scanning.

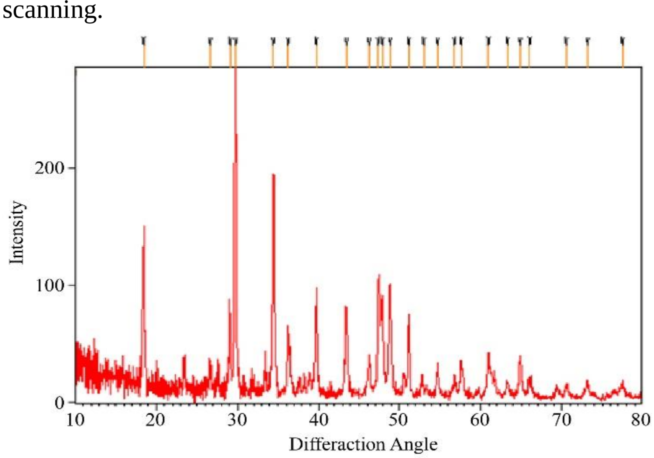


Fig. 2 Diffraction pattern of the Sol-gel-grown CaO in X-rays

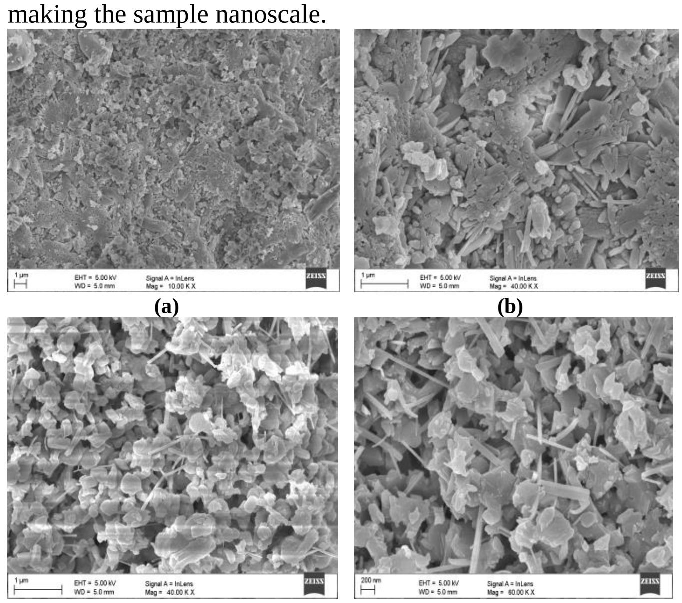
As shown in Figure 2, the XRD analysis of nano lime shows various important structural features of the material. Interestingly, the XRD spectrum shows a much weaker peak value, suggesting that the material is growing into tiny (nanoscale) crystals. Because of their decreased intensity, the sample particles seem far smaller than their macroscopic counterparts. Further, the XRD graph indicates that the sample has two different phases that are visible within the XRD range: CaO and Ca.

The XRD pattern's principal peaks are closely associated with the typical peaks of CaO (JCPDS No. 821691), $CaCO_3$ (JCPDS No. 5586), and Ca $(OH)_2$ (JCPDS No. 010735492). Importantly, the sample is completely pure because no contaminants were discovered during analysis.

As well as signifying that some Ca is in the sample, the XRD findings reveal the nanocrystalline emergence of CaO in the material. Results from these experiments help clarify the main features and components found in nano lime and allow for further studies in various fields.

Precise measurement of features and size is essential to know the physical properties and purposes of CaO produced by sol-gel. This study used FESEM to examine the nano lime, and the resulting images are shown in Figure 3 at several magnifications.

At the higher zoom level of 200 nanometers, visible structural characteristics of the CaO nanoparticles can be seen in Figure 3(d). It becomes obvious from the figure that CaO particles are shaped as rods and spikes, with each rod having a linear pattern. Importantly, testing revealed that the component rods and particles are in the nanometer range, making the sample nanoscale.



(a) (b) (c) (d)

Fig. 3 Images of FESEM of nano lime at varying magnification (a) 10x, (b) 40x, (c) 40x, and (d) 60x.

Furthermore, the FESEM images reveal a highly porous and agglomerated rod-like growth of the material, emphasizing the intricate and porous nature of the nano lime structure. This thorough analysis substantiates the conclusion that the prepared nano lime is free from impurities and consists of nano-sized particles, which hold significant promise for various applications due to its unique size and morphology.

2.2. Methodology

A step-by-step procedure to mix and test soils is shown in Figure 4. This research has three key processes, particularly in the mixing and testing of materials. The first is the preparation of soil, the second is the preparation of fly ash, and the third is the preparation of nano lime. Mixing is done up to the point when the nano lime and fly ash are mixed uniformly with the soil. Moreover, the physical and engineering tests are conducted to verify the soil properties.

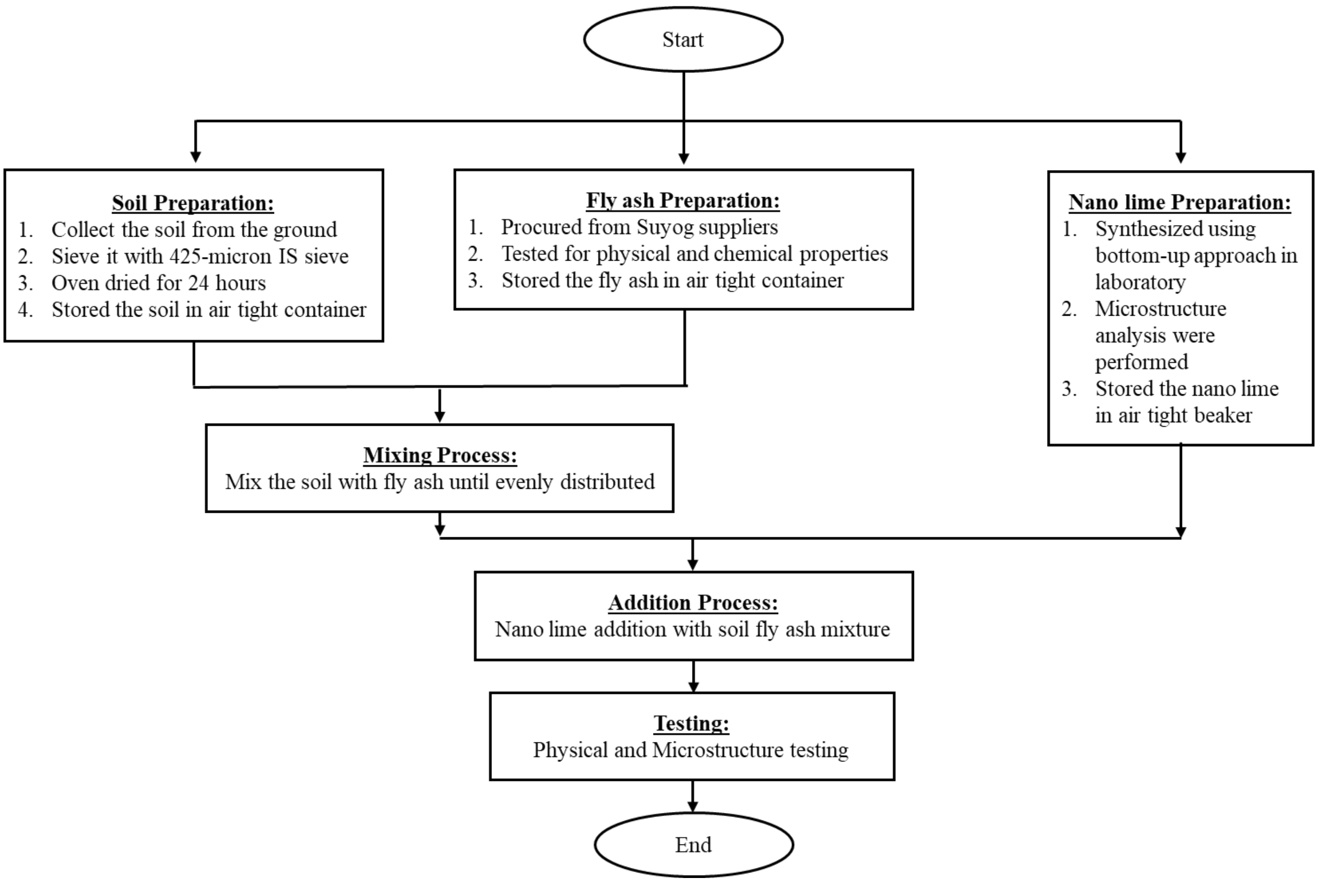


Fig. 4 The mixing and testing processes in a flowchart

To perform this soil stabilization, dry fly ash was blended with oven-dried black cotton soil that had been sieved to 75 microns and mixed in proportions from 40% to 80%, with every change occurring every 20% of the total mixture. More mixing took place as long as the texture and color were not the same. Subsequently, a liquid nano lime that had been diluted in water to the correct moisture was put into the mixture. Once all preparations were complete, this composite material was set to develop. Black cotton soil is made more useful for construction by adding fly ash and nano lime, which may reduce both erosion and soil settlement, forming a more durable and stable ground.

The testing program was carried out following the rules set out by the Indian Standard (IS) when the mix was made from expansive soil, fly ash and nano lime. The experimental program monitored important soil properties by measuring Atterberg's LL, PL, and SL limits. Besides, the swell pressure and free swell index (FSI) were evaluated because they indicate how much the soil can expand and take on water. The test outcomes help explain how stabilizing the technique works and its usefulness in building applications.

3. Results and Discussion

3.1. Atterberg Limit Test

The performance of the Atterberg Limit Test on Rajkot soil before and after treatment is illustrated in Figure 5-7, which provides valuable data. When fly ash is added to soil at higher concentrations, its plastic limit increases and the liquid limit decreases. Because of this unique phenomenon, the soil's behavior changes noticeably due to a lower plasticity index. The plasticity index is most helpful in finding out how well soil can handle different building and geotechnical workloads. As a result of this tendency, adding fly ash to soil improves its ease of handling, protects it against excessive moisture, and makes it better for engineering work.

The addition of nano lime to fly ash and expanding soil greatly alters the soil's particle size category. The size of clay particles found in the soil tends to increase. For that reason, the soil goes from high plasticity silt (MH) to high plasticity clay (CH). There is a clear sign that this transition makes nano lime very valuable for changing the soil's small-scale structure. The reason for this transition is shown clearly by the close connections among fly ash, nano lime and clay soil particles as seen in Figure 13 (c). This work confirms that nano lime can be used to adjust soil characteristics for diverse geotechnical applications. The similar applications of fly ash, nano lime, and nano $CaCO_3$ have all been seen in earlier studies [1, 11, 13].

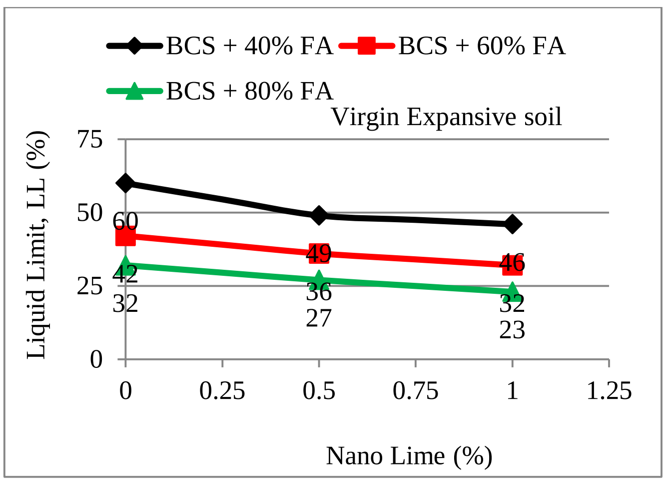


Fig. 5 Liquid limit effect of expansive soil treated by nano lime and fly ash

One important characteristic that defines A soil's maximum shrinkage is determined by its volume change behavior. An important aspect of geotechnical engineering, especially when it comes to building projects, is the property's inferred capacity for soil swelling. The impact of fly ash addition into the soil results in a notable change in the value of the shrinkage limit, which is supported by the findings of this study, which are presented in Figure 8. The study shows that the shrinkage limit value increases by an astounding 177% when fly ash replaces eighty percent of the soil. This suggests that reducing the soil's capacity to swell can be greatly aided by replacing a large portion of the soil with fly ash. However, in comparison to the expansive virgin soil, other samples show a rise in the shrinkage limit of between 100% and 155%. This implies that a considerable reduction in soil swelling is achieved at even lower fly ash replacement levels. When nano lime is combined with 40% fly ash and soil, the shrinkage limit is found to increase considerably [11]. We observe this remarkable increase because of the action of nano lime, combined with the silicates within the expanding soil and fly ash. Results from these experiments match findings by other researchers in this field and could lead to more stable soils in construction work.

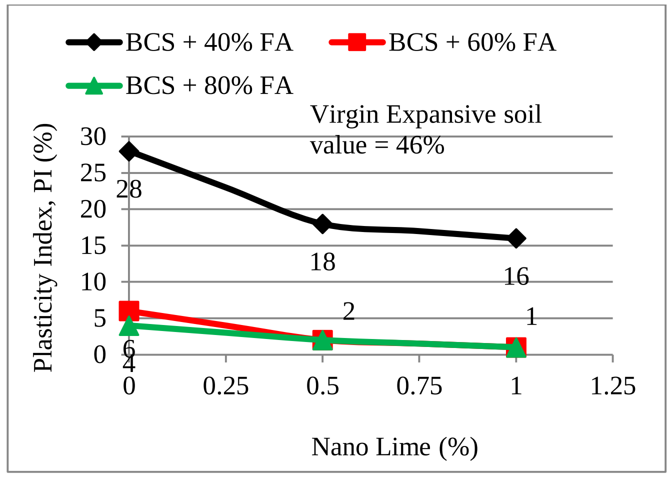


Fig. 6 Plasticity index effect of expansive soil treated by nano lime and fly ash

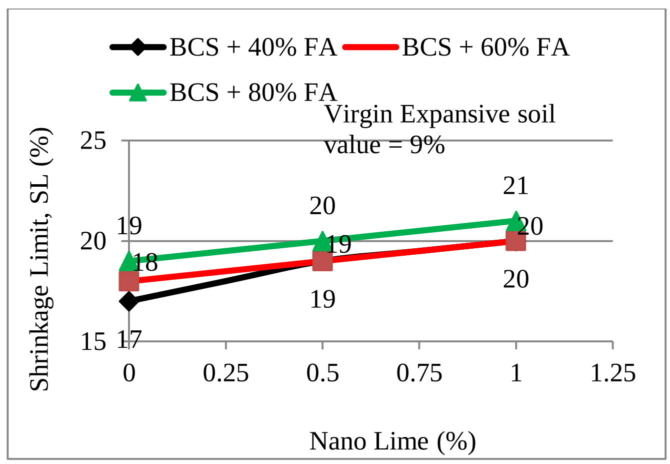


Fig. 7 Shrinkage limit effect of expansive soil treated by nano lime and fly ash

Since the shrinkage limit value rose by a marginal amount, fly ash replacement clearly plays a big role in limiting soil swelling, mainly at 80%. Chemical interactions caused by nano lime result in significantly stronger enhancement in the reduction limit values of a 40% fly ash and soil mixture. These studies, in addition to similar findings by others [11, 13], increase our understanding of soil behaviour and can be put to use making soils more stable for buildings.

3.2. Free Swell Index

The Free Swell Index was analyzed with reference to the Indian Standard Code of Conduct. Findings are presented that provide details on the resulting changes when soil is replaced with non-cohesive fly ash.

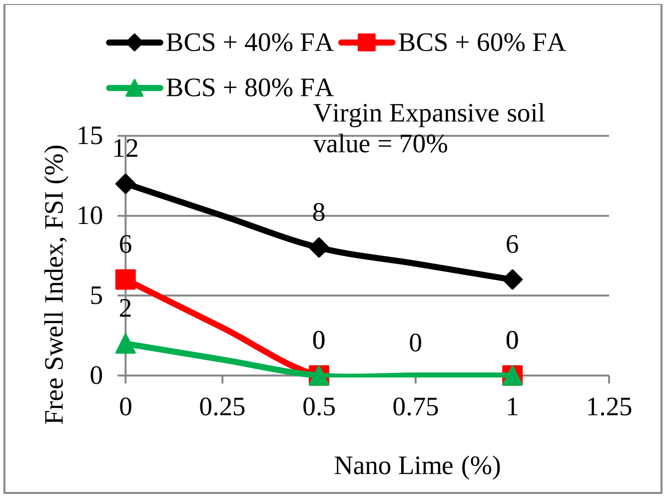


Fig. 8 Free swell index effect of expansive soil treated by nano lime and fly ash

Fly ash replacement in larger amounts resulted in a marked drop in the free swell index, finally reaching zero. The above outcome can be interpreted by the fact that fly ash particles are larger and less reactive than usual clay particles. The findings indicated that including nano lime in the mixtures resulted in the swelling index becoming zero for each composition.

The reason for such big improvements is the healing period. As the curing period was increased, more soil particles were involved in a chemical reaction with nano lime, which boosted the formation of calcium-silicate-hydrates. As a result, the expansion value declined a lot, suggesting important progress in controlling soil swelling. It has great prospects for being used in geotechnical engineering to stabilize soil. The findings here show that we can make our infrastructure and construction better and more environmentally friendly since new safety possibilities for dealing with soil have been revealed.

3.3. Swell Pressure Tests

Swell pressure tests play an important role in the study by helping researchers understand how expansive soil and treated soil samples change in volume and what stress changes they experience. It is evident in Figure 9 that the presence of a small amount of nano lime greatly reduces swell pressure, in some cases by more than 90%. It explains the extraordinary role of nano lime in solving the swelling problems seen in expansive soils. When the fly ash quantity in the mixture is increased, the usually reduced swell pressure is lower by at least half. The results demonstrate that including fly ash in virgin soil can help prevent soil from expanding [1, 11, 13].

Mixing nano lime and fly ash, as these results show, has the potential to improve engineering solutions for problems like unstable structures and rising soil, as well as ground heaving. In general, the findings suggest that such additive materials have a significant impact on the swelling of the soil and improve its construction and geotechnical-related properties.

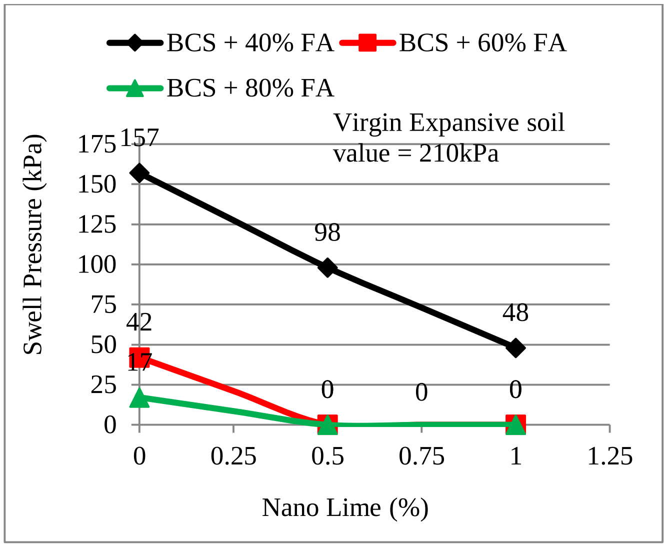


Fig. 9 Swell pressure effect of expansive soil treated by nano lime and fly ash

Thus, after treating fly ash nano lime combination on expansive soil, the liquid limit decreases up to 58%, plasticity index reduces up to 89%, free swell index reduces up to 100%, and swelling pressure reduces up to 94%. As a result, the shrinkage limit increases up to 177%.

3.4. Microstructural Analysis

3.4.1. Microstructural Characterization of Soil Using FESEM-EDS

Combining the FESEM and EDS technology provides a sophisticated way to analyze the structure and chemistry of soil samples. Using the Carl Zeiss Model Supra 55, the technology supplies remarkable detail about soil properties. Examining the surface at the nanoscale using a strong beam of electrons, FESEM helps produce detailed images of soil samples.

A close look at microstructures in the soil, specifically organic matter, pores and mineral grains, is provided by Figure 10 (a) to (h) with different magnification level ranging from 10 to 100. With these microstructures, one can identify the features of texture and particle structures in the soil. Because EDS can detect and evaluate many substances, it is applied to study the chemical composition of soil.

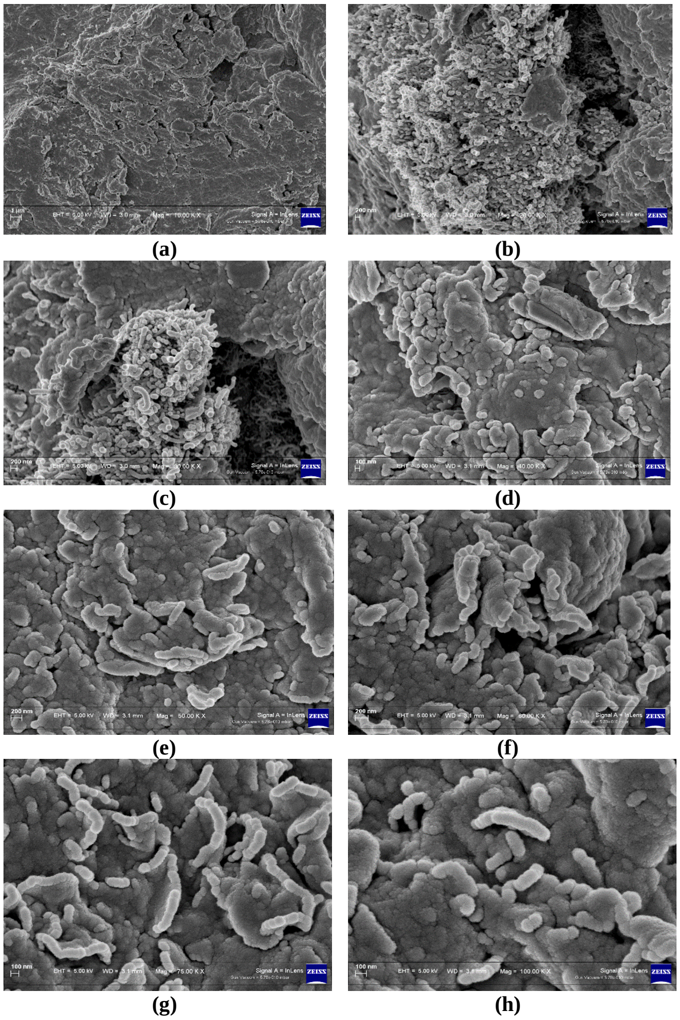


Fig. 10 Images were examined with a Field Emission Scanning Electron Microscope

By taking X-rays from soil samples under an electron beam, EDS makes it easier to identify chemical components as well as minerals, pollutants or trace elements in the soil. Due to its combination of FESEM and EDS, the Carl Zeiss Model Supra 55 will greatly assist soil scientists, geologists and researchers in evaluating soil properties and conducting monitoring.

3.4.2. Microstructural Characterization of Soil Using X-ray Diffraction Analysis

X-ray diffraction analysis, called XRD, is used to obtain full details on what a material is made of, its appearance and how it crystallizes. The basis for the technique is the constructive interaction between crystalline samples and monochromatic X-rays. To perform this experiment, we applied models to specially crafted datasets called "Dataset 3" and "Dataset 4". Mineral and crystal forms of substances, such as soil, are studied through the process of X-ray Diffraction (XRD). XRD shows what minerals are in black cotton soil and how much of each is present. Using this data helps experts understand how soil acts and what features it has. A graphical presentation can be found in Figure 11.

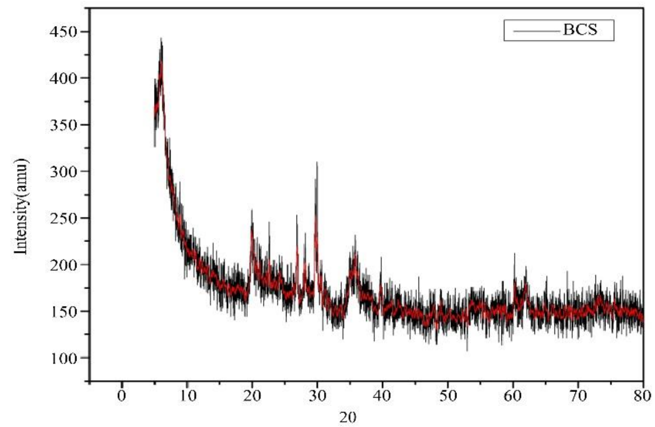


Fig. 11 Black cotton soil intensity and 2θ

Black cotton soil combined with fly ash can be studied using XRD analysis to determine what minerals are present and how they are arranged. A reliable approach to discovering and quantifying crystalline phases in a sample is XRD. A representation of the graph is shown in Figure 12.

3.4.3. Microstructural Characterization of Soil Using Scanning Electron Microscope

Scanning Electron Microscope (SEM) imagery has helped us better see how fly ash and nano lime interact with various soil stabilization mixtures. Three distinct samples, the virgin soil sample, soil samples with 60% fly ash content, and soil samples with 60% fly ash content and 1% nano lime, are studied in Figure 13 (a), (b), and (c). Early-stage hydration events are accelerated, and catalytic reactions inside the materials are enhanced by nano lime, whose large specific surface area allows for this. These initial reactions then set off pozzolanic reactions, which cause the components of the sample to link and form a composition that is robust, long-lasting, low-permeability, and dense.

The interactions between nano lime and the soil and fly ash combination are clearly visible in the SEM pictures. Together with the silica from the soil and fly ash, nano lime fills the empty nanometre spaces to create silicate-Calcium-Hydrate Clusters (CSH). As shown in Figure 13 (c), CSH nanostructures begin to appear in the soil fabric and the soil structure is greatly altered. You can certainly see that soil is improved by its contact with nano lime, since the resulting bond between soil particles significantly increases the engineering qualities of the soil. As a result, the material becomes more suitable for several construction and soil stabilization purposes thanks to a denser and rugged surface layer and stronger internal bonds. The SEM study reveals that using nano lime helps build stronger, more sustainable materials from a soil and fly ash blend.

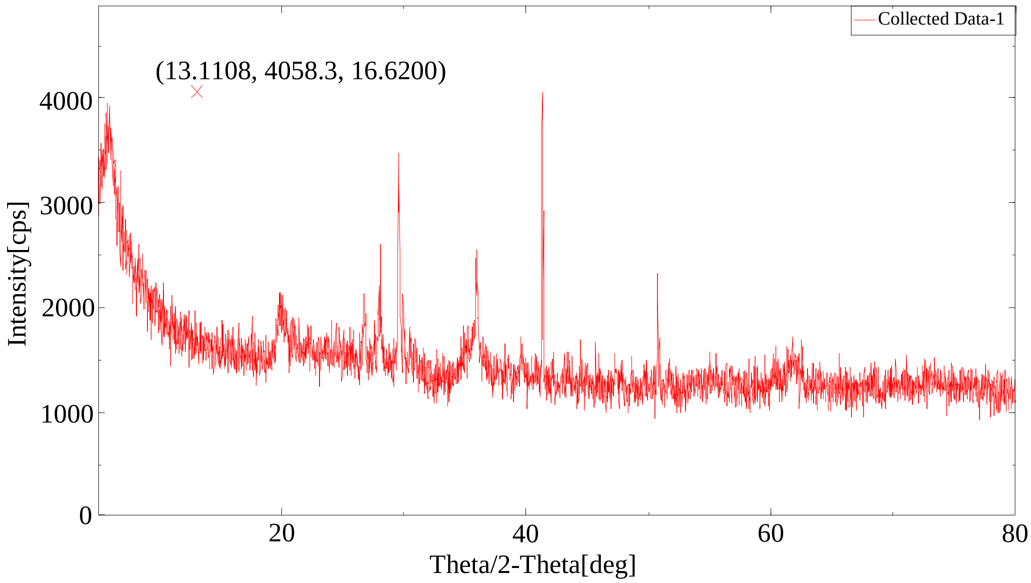
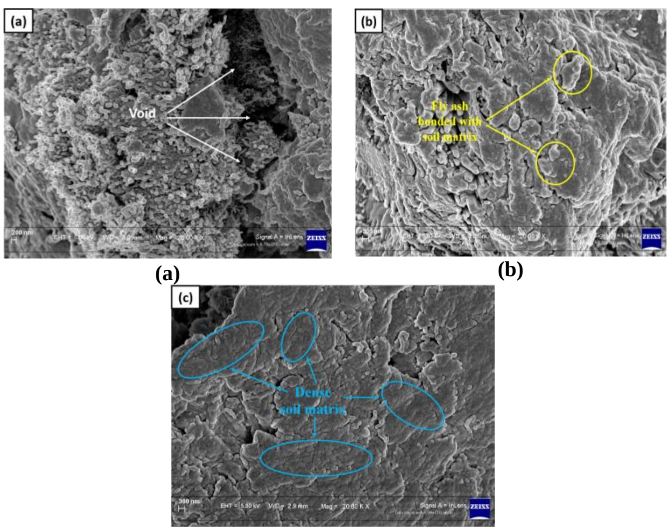


Fig. 12 Sample of black cotton soil with fly ash intensity and 2θ



(a) (b)

(c)

Fig. 13 FESEM images of three soil specimens with different proportions

4. Conclusion

The research examines the interaction between nano lime and high-volume fly ash used in expansive soils. Using the extensive testing program performed in this study, several significant points can be concluded. (i) Nano lime shows great potential in managing the swelling problem with expansive soil, and using fly ash increases its effectiveness. When used alone, neither fly ash nor nano lime results in major swelling changes in the soil. (ii) Swelling control increases as the amount of both nano lime and fly ash increases. When these additives are included in greater proportions, the soil becomes much better able to resist swelling. (iii) When comparing the impact of several swelling characteristics on the blend, the mix with 1% nano lime and 80% fly ash is discovered to be the best option for reducing swell-shrink issues and stabilizing the land. (iv) Microstructural support of these improvements is seen through FESEM, EDS and XRD studies to show the generated Calcium Silicate Hydrate (CSH) bonds, increased packing and densification of the soil particles and a significant decrease in pore connectivity.

The paper, therefore, validates that the synergistic effect between nano lime and high-volume fly ash greatly improves the engineering characteristics of expansive soils through a change in their microstructure. Engineers and contractors serving vast soil areas can use this combination to prepare more lasting foundations and subgrades.

The stabilization approach complies well with the sustainability objectives, considering that it can lead to the use of waste as well as minimize soil replacement. The proposed soil stabilization technique presents a locally based, environmentally acceptable and technically viable solution to difficult expansive soils.

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