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# Investigation on use of Nano clay for Sustainable Subgrade Construction

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## ABSTRACT

This study examines the effectiveness of nanoclay in stabilizing clayey soil through laboratory testing. Key parameters, including Unconfined Compressive Strength (UCS) and Atterberg limits, were evaluated to assess the impact of nanoclay addition. The soil sample used in this research was classified as highly plastic clay. Nanoclay was synthesized through a green synthesis approach, involving the pulverization of the clayey soil into Nano-sized particles. To understand the stabilization mechanism, X-ray Diffraction (XRD) and Scanning Electron Microscopy (SEM) analysis were conducted.

The findings demonstrate a significant improvement in the mechanical properties of the soil when mixed with nanoclay. SEM imaging and particle size analysis confirmed the successful production of nanoclay through milling. Various proportions of nanoclay (ranging from 0% to 4% in 0.5% increments) were incorporated into the soil. The study had three primary objectives: (i) to evaluate the compressive strength of different nanoclay percentages in clayey soil, (ii) to determine the Atterberg limits, including liquid limit (LL), plastic limit (PL), and plasticity index (PI) and (iii) Pavement design based on soaked CBR values and cost optimization.

Results revealed that incorporating 3% nanoclay yielded the most significant improvement in soil strength. The enhanced performance was attributed to the pozzolanic reactions induced by the nanoclay, leading to improved soil stabilization. Additionally, the use of nanoclay in subgrade stabilization contributed to cost reduction by minimizing pavement crust thickness. Overall, the findings highlight the economic and structural benefits of utilizing nanoclay for soil stabilization.

**Keywords:** Clayey soil, Nanoclay, Soil stabilization, Mechanical properties, Unconfined compressive strength.

## 1. Introduction

Soil is a fundamental material in civil engineering, serving as a key component in the construction of various infrastructure projects. However, the inherent properties of certain soil types especially clayey soils pose challenges due to their low bearing capacity, high compressibility, and limited strength. These geotechnical limitations necessitate the adoption of improvement techniques to enhance soil performance. Among the various strategies explored, the use of stabilizing agents or admixtures has emerged as a prominent solution (Heidarzadeh & Kamgar, 2020a, b; Jafarzadeh & Zamanian, 2014, 2018). With the rapid advancement of nanotechnology, nanomaterials have gained considerable attention in the field of civil engineering. Their unique physicochemical characteristics open up new possibilities for soil modification and stabilization (Daniyal et al., 2018; Javadzadeh, 2019). The widespread development and availability of nanoproducts have facilitated their application across multiple engineering disciplines, including geotechnical engineering (Nabizadeh Rafsanjani & Kadivar, 2011). A growing concern in traditional soil stabilization practices is the environmental impact caused by chemical additives. In contrast, nanoclays present an environmentally friendly alternative. Not only do they contribute to the improvement of soil properties, but they also exhibit the capacity to absorb environmental pollutants, offering dual benefits in terms of sustainability and performance (Ouhadi & Amiri, 2011). Nanoclays are naturally occurring nanostructured minerals, typically possessing a high specific surface area of approximately 750 $m^2/g$ (del Hoyo et al., 1996). Their remarkable surface reactivity and ion exchange capacity make them highly effective in improving mechanical strength when used as a stabilizing agent. Gallagher and Lin (2005) highlighted that the incorporation of nanoclays in composite materials significantly enhances their strength due to these attributes. Based on their chemical composition and morphology, nanoclays are generally classified into montmorillonite, bentonite, kaolinite, hectorite, and halloysite (Niroumand et al., 2013). Empirical studies have validated the positive influence of nanoclays on soil performance. For instance, Niroumand et al. (2013) reported a 4.8-fold increase in the compressive strength of bricks when 5% kaolinite nanoclay was added. Similarly, Khalid et al. (2015) observed substantial improvements in soil behavior by incorporating 3% nanoclay, including increases in liquid and plastic limits (by 13% and 44%, respectively), a reduction in plasticity index (by 17%), a 15% increase in compressive strength, and a 10% rise in the internal friction angle. In another relevant study, Tabarsa et al. (2018) investigated the stabilization of Loess soils using nanoclays, conducting both laboratory and field evaluations. Their results demonstrated that even a small addition (0.5–3%) of nanoclay significantly altered soil behavior improving plasticity and stiffness, while affecting parameters such as optimum moisture content, dry density, and friction angle. The collective findings from past research underscore the potential of nanoclays as effective soil stabilizers, especially for problematic soils. In this study, the focus is on evaluating the effects of bentonite nanoclay in varying proportions on key geotechnical parameters such as specific gravity, compressive strength, and shear strength. The soil samples were first characterized using standard laboratory tests, including sieve analysis, hydrometer testing, Atterberg limits, and specific gravity determination. The results of these experiments are discussed in detail in the subsequent sections to highlight the suitability of nanoclay in sustainable subgrade construction.

## 2. Methodology

Improvement of Atterberg limits, specific gravity, unconfined compressive strength and California Bearing Ratio of clayey soil with nanoclay, Figure 1 presents the methodology adopted for this study, illustrating the sequential process of improving the geotechnical behavior of clayey soil through nanoclay treatment. It encapsulates the sample preparation, characterization of untreated soil, mixing of nanoclay in varying proportions, followed by laboratory testing to assess the resultant improvements. This structured approach ensures a comprehensive evaluation of the influence of nanoclay on soil stabilization.

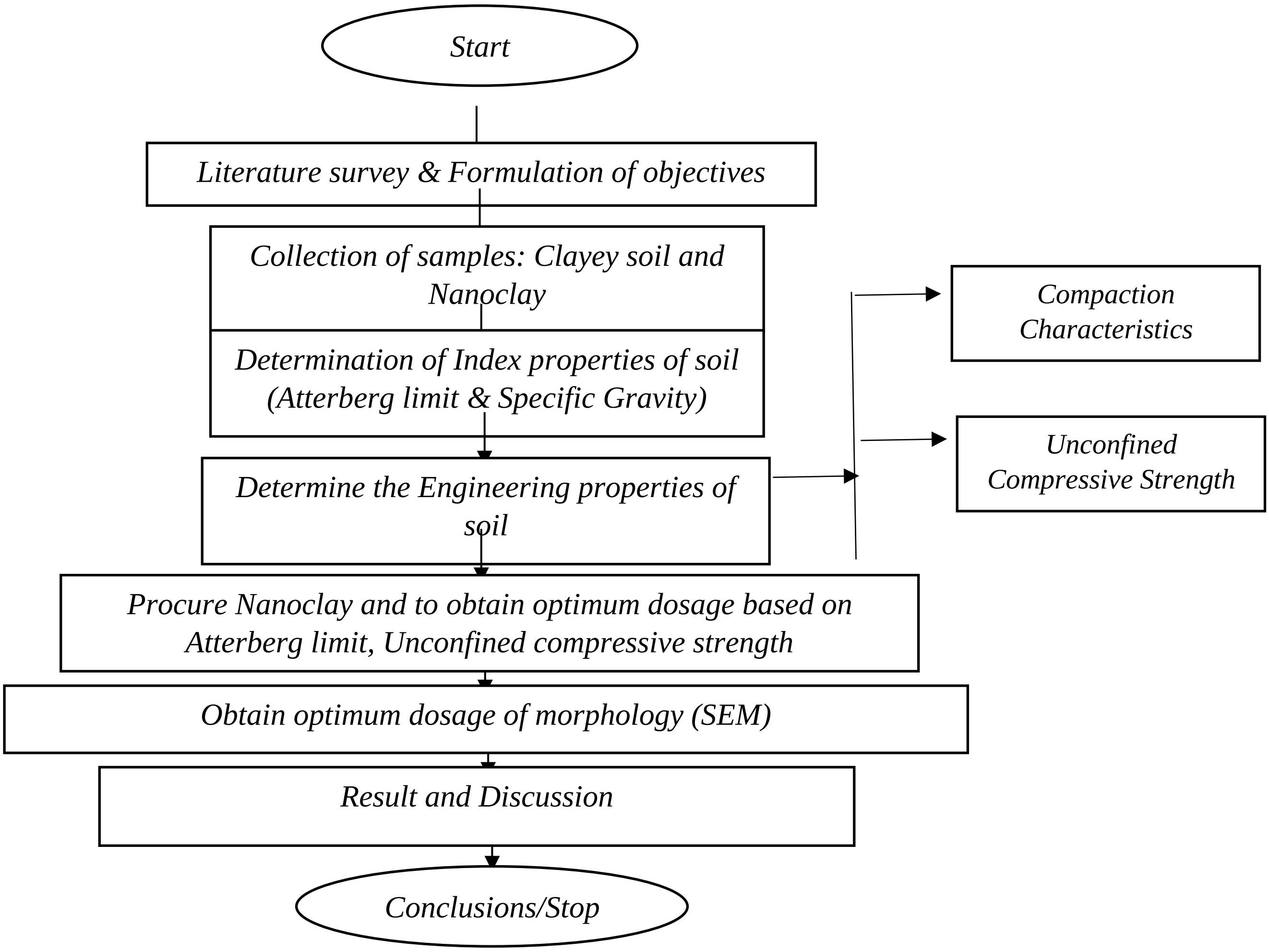


Figure 1 The process of improvement of clayey soil and nanoclay flow chart

### 2.1 Clayey Soil Sample:

The clayey soil utilized in this study was sourced from the campus of The ICFAI University, Dehradun, located in Selaqui, Dehradun, India (Latitude: 30°21′N, Longitude: 77°52′E). Samples were collected from a depth of 2 meters below ground level in both disturbed and undisturbed forms. To preserve their natural moisture content, the samples were immediately sealed in airtight plastic wraps and stored at room temperature (approximately 27°C) in the geotechnical laboratory. The physical and engineering characteristics of the collected soil were determined following the procedures outlined in IS: 2720 (Part 7, 10, 16, 40). Furthermore, to analyze the chemical composition of the soft clayey soil, an X-Ray Fluorescence (XRF) test was conducted, offering insights into the elemental makeup crucial for understanding soil behavior in stabilization applications.

### 2.2 Nanoclay Sample:

The nanoclay used in this investigation was synthesized in the laboratory through a green synthesis method, employing plant extracts to produce eco-friendly nanoclay particles. The synthesized nanoclay exhibited particle sizes in the range of 1–100 nanometers. The green synthesis process involved exfoliating and stabilizing clay particles using bioactive compounds present in the plant extracts, serving as reducing and capping agents. While this method offers environmental advantages by avoiding hazardous chemicals, it is acknowledged that the properties of nanoclay derived through this route may differ from those produced using conventional mineral-based processes. Nonetheless, the green approach aligns with sustainable construction practices. The chemical composition of the synthesized nanoclay was determined using X-Ray Fluorescence (XRF) analysis, providing essential data for evaluating its suitability in geotechnical applications.

### 2.3 Sample Preparation and Testing:

The required amount of nanoclay for each test specimen was calculated by multiplying the designated nanoclay percentage by the total dry weight of the clayey soil. The detailed mixture proportions are presented in Table 1. Following the method recommended by Taha and Taha (2012), a two-stage mixing process was adopted in this study to ensure homogeneity of the soil-nanoclay blend. In the first stage, the total dry soil quantity was manually divided into ten equal portions. Each portion was evenly spread within a 100 × 100 cm square steel pan. The appropriate amount of nanoclay, corresponding to each mixture, was then evenly distributed over the soil using a 0.075 mm sieve, as illustrated in Figure 2.

Subsequently, in the second stage, all the portions were thoroughly blended using a horizontal cylindrical mixer for at least 30 minutes to achieve a uniform mixture. To prevent segregation and enhance uniform hydration, the predetermined quantity of water was immediately added to the soil–nanoclay mix. The mixture was then sealed in airtight plastic bags and kept undisturbed for 24 hours to allow proper moisture absorption and particle interaction.

A total of nine specimens were prepared, as detailed in Table 1. The first specimen, containing 0% nanoclay, was considered the control sample. The remaining eight specimens were prepared by incrementally increasing the nanoclay content from 0.5% to 4.0% in steps of 0.5%. These prepared samples were also subjected to Scanning Electron Microscope (SEM) analysis to observe the microstructural changes and particle arrangement influenced by nanoclay addition. Geotechnical testing including the Unconfined Compressive Strength (UCS) test and Atterberg Limit test was conducted on each specimen following the procedures prescribed in IS: 2720 (Part 10).

Table 1 Mix proportion for nanoclay (by % weight of dry soil)

| Abbreviation | Mix Content |
|---|---|
| A1 | 0.0% NC* + 100% CS** |
| A2 | 0.5% NC + 99.5% CS |
| A3 | 1.0% NC + 99.0% CS |
| A4 | 1.5% NC + 98.5% CS |
| A5 | 2.0% NC + 98.0% CS |
| A6 | 2.5% NC + 97.5% CS |
| A7 | 3.0% NC + 97.0% CS |
| A8 | 3.5% NC + 96.5% CS |
| A9 | 4.0% NC + 96.0% CS |

*NC = Nanoclay, **CS = Clayey soil

Figure 2 Homogeneous sample preparation

## 3. Experimental Results

### 3.1 Clayey Soil Properties:

The results of the physical properties of soft soil samples are presented in Table 2. The analysis indicates that, in its natural state, the water content of the soft soil is 134.5%, with a specific gravity of 2.37. Based on particle size distribution, the soil sample consists of 3.08% sand, 7.20% silt, and 89.72% clay. The plastic limit and liquid limit are 22.70% and 45.30%, respectively, yielding a plasticity index of 22.60%. According to these properties, the soil sample is classified as highly plastic clay.

The chemical composition of the soft soil, determined through X-ray fluorescence (XRF) analysis, is presented in Table 3. The results indicate that the clayey soil exhibits pozzolanic properties, as it contains a high percentage of key constituents such as silicon dioxide ($SiO_2$), aluminium oxide ($Al_2O_3$), and ferric oxide ($Fe_2O_3$).

Table 2 Physical properties of soft soil sample

| Properties | Values |
|---|---|
| Natural moisture content, w (%) | 134.5 |
| Specific gravity (G) | 2.37 |
| Plastic limit (%) | 22.70 |
| Liquid limit (%) | 45.30 |
| Plastic index (%) | 22.60 |
| Optimum moisture content (%) | 27 |
| Maximum dry density (mg/m$^3$) | 1.24 |
| **Particle size distribution** | |
| Gravel (%) | 0 |
| Sand (%) | 3.08 |
| Silt (%) | 7.20 |
| Clay (%) | 89.72 |
| Soil classification (USCS) IS:1498 | Clay soil of high plasticity (CH) |

Table 3 Chemical composition of clayey soil sample

| Chemical Elements | Concentration (%) |
|---|---|
| $SiO_2$ | 65.69 |
| $Al_2O_3$ | 19.12 |
| $Fe_2O_3$ | 8.34 |
| $K_2O$ | 3.75 |
| MgO | 1.71 |
| $Na_2O$ | 0.68 |
| CaO | 0.35 |
| MnO | 0.18 |
| $TiO_2$ | 0.11 |
| $P_2O_5$ | 0.07 |

### 3.2 Nanoclay Properties:

Nanoclay samples in powdered form were obtained through a milling process and subsequently tested for particle size distribution. Particles are classified as Nano sized when their diameters fall within the range of 1–100 nm Taha MR (2009). As shown in Figure 3, the particle size distribution confirms that 100% of the particles in a 1gm sample fall within the nanoscale range following the milling process. This result confirms that the material can be categorized as nanoclay and is suitable for soil modification applications.

The chemical composition of the nanoclay, presented in Table 4, reveals a composition very similar to that of the original clayey soil. The nanoclay retains pozzolanic characteristics, primarily due to the presence of significant proportions of silicon dioxide ($SiO_2$), aluminium oxide ($Al_2O_3$), and ferric oxide ($Fe_2O_3$) the major constituent compounds responsible for its reactivity.

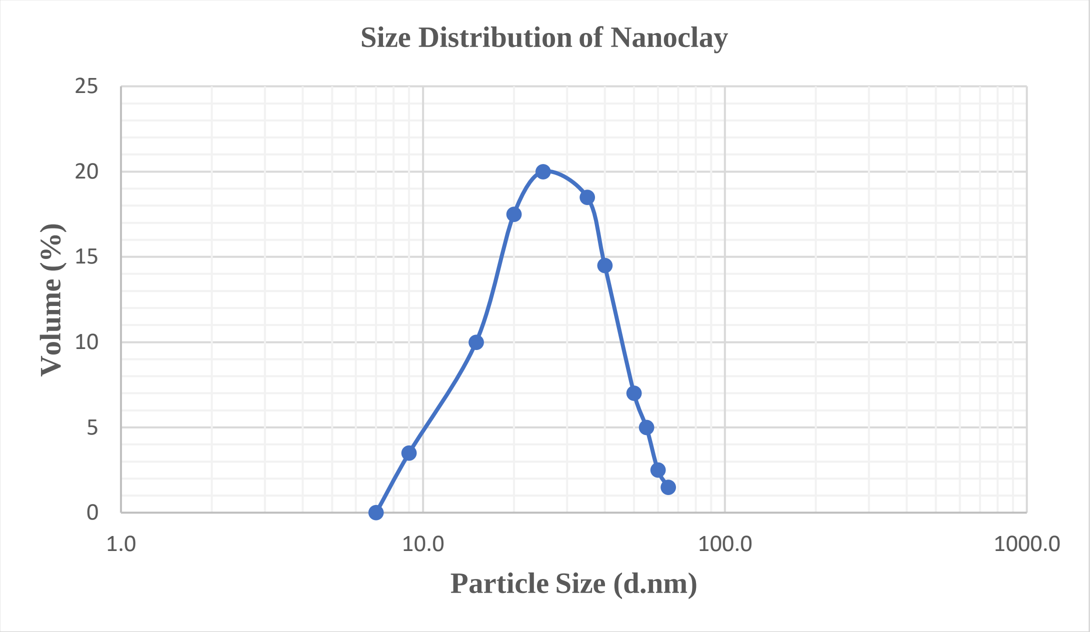


Figure 3 Particle size (d. nm) distribution for nanoclay

Table 4 Chemical composition of nanoclay

| Chemical Elements | Concentration (%) |
|---|---|
| $SiO_2$ | 69.27 |
| $Al_2O_3$ | 20.02 |
| $Fe_2O_3$ | 9.14 |
| $K_2O$ | 0.57 |
| MgO | 0.13 |
| $Na_2O$ | 0.21 |
| CaO | 0.19 |
| MnO, $TiO_2$, $P_2O_5$ | 0.47 |

## 4. Results and Discussion

### 4.1 X-Ray Diffraction (XRD) Analysis

X-ray diffraction (XRD) analysis was performed on powdered specimens to investigate the crystallographic structure and assess the degree of intercalation and exfoliation of nanoclay within the clayey soil matrix. Bragg's Law ($n\lambda = 2d \sin\theta$) was applied to calculate the interplanar spacing (d-spacing), offering insights into the structural changes induced by nanoclay addition. The XRD study included pure nanoclay samples and clayey soil mixed with 0.5%, 1.5%, and 3% by weight of nanoclay. As shown in Figure 4, the pure nanoclay exhibited a sharp and intense diffraction peak at $2\theta = 5.90°$, indicative of well-ordered silicate layers. However, for the clayey soil nanoclay mixtures, especially at 0.5% and 3% nanoclay content, the characteristic peak intensity decreased significantly and shifted to $2\theta = 3.30°$. This shift, along with the observed increase in interlayer spacing, suggests a combination of intercalated and agglomerated structures, reflecting partial exfoliation of the silicate layers.

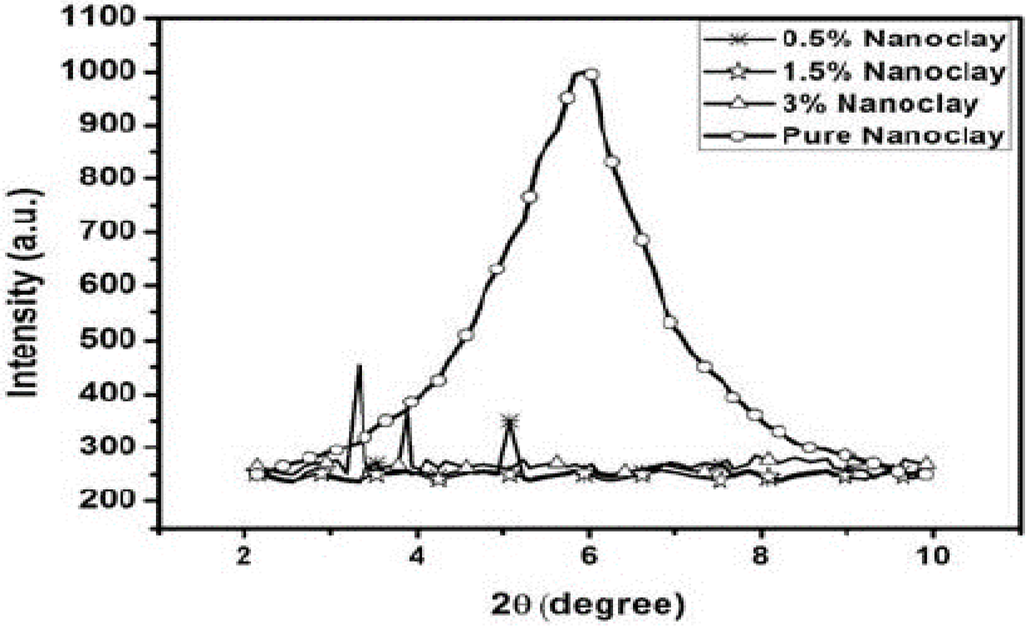


Figure 4 X-ray diffraction (XRD) pattern of pure nanoclay, 0.5% wt., 1.5 % wt. and 3 % wt. Nano-clay.

## 4.2 Microstructural Analysis Using SEM:

The three-dimensional arrangement and fabric of clayey soil particles were examined using a Scanning Electron Microscope (SEM) due to its high-resolution capability and extensive depth of focus. As illustrated in Figure 5, the microstructure of natural clay soil observed at 2500× and 6000× magnification exhibits a flaky morphology with a dispersed fabric. The particles appear irregularly shaped, with a more open structure and wider spacing between individual particles.

In contrast, Figure 6 presents the SEM images of clayey soil mixed with 3% nanoclay, observed at 6000× and 10,000× magnification. The micrographs reveal a more cohesive and compact mass, resulting from the interaction between the clayey soil and nanoclay. The addition of nanoclay significantly enhances the surface area available for particle interactions, leading to improved bonding and a more uniform structure. This microstructural transformation contributes to enhanced engineering properties of the soil, including a smoother surface texture and denser particle arrangement.

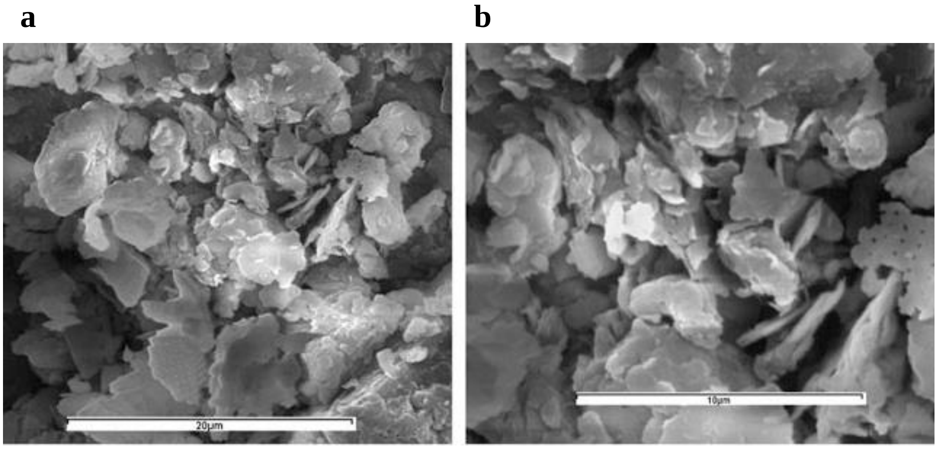


Figure 5 Microstructure of clayey soft soil. [a- Magnification at 2500x. b- Magnification at 6000x]

**c** **d**

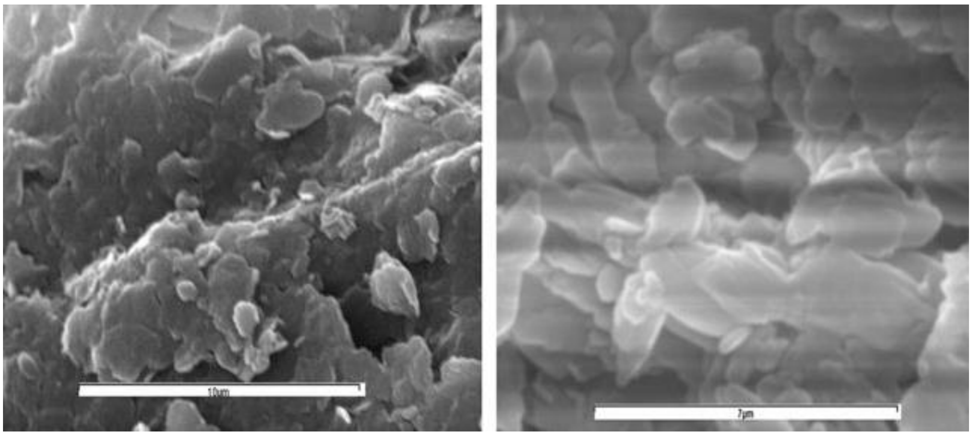


Figure 6 Microstructure of 3 % nanoclay mixed with clayey soil. [a- Magnification at 6000x. b- Magnification at 10,000x]

### 4.3 Stress Strain Relationship and Compressive Strength:

Figure 7 illustrates the relationship between axial strain and deviator stress for both the natural clayey soil (control sample) and the clayey soil mixed with 0.5% to 3% nanoclay. The graph clearly demonstrates that the maximum shear strength of the soil improved with the addition of nanoclay, accompanied by a reduction in axial strain compared to the control sample.

Further, Table 5 presents the corresponding maximum compressive strength values shown in Figure 8. The results indicate a significant enhancement in compressive strength with just 3% nanoclay addition. This improvement highlights the effective role of nanoclay, even in small quantities, in reinforcing the clayey soil matrix. The observed increase in strength can be attributed to the strong interfacial bonding and improved interaction between the nanoclay particles and the clay soil, which contributes to a denser and more cohesive microstructure.

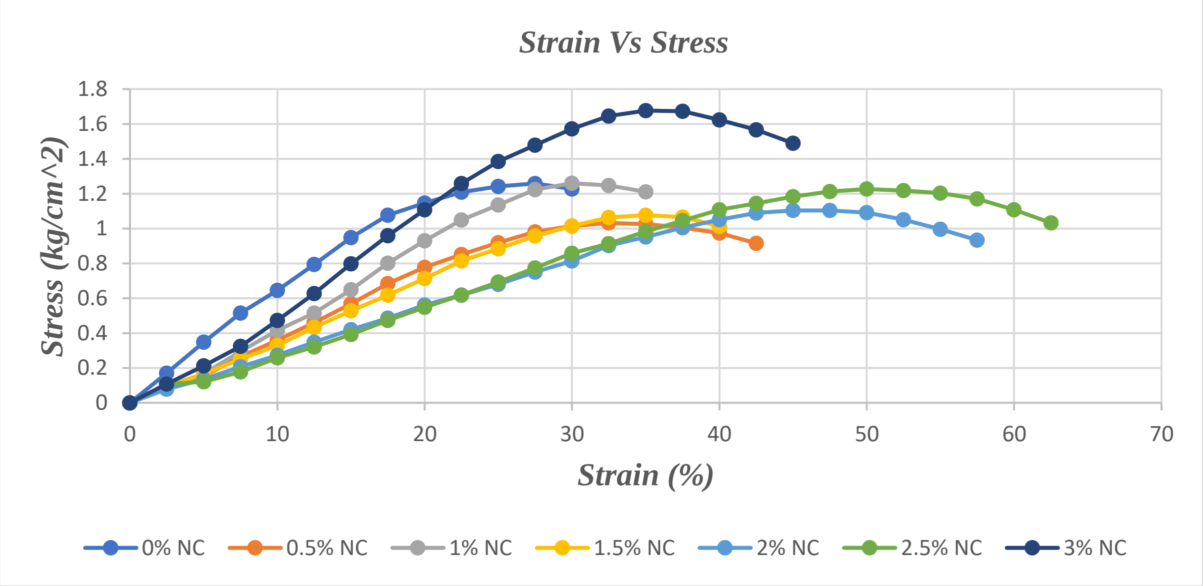


Figure 7 Stress - Strain graph of nanoclay mixture

Table 5 Result of compressive strength clayey soil mixed with nanoclay

| Abbreviation | Mix Content | Compressive strength (kPa) |
|---|---|---|
| A1 | 0.0% NC + 100% CS | 231.4 |
| A2 | 0.5% NC + 99.5% CS | 243.7 |
| A3 | 1.0% NC + 99.0% CS | 255.0 |
| A4 | 1.5% NC + 98.5% CS | 260.9 |

| | | |
|---|---|---|
| A5 | 2.0% NC + 98.0% CS | 262.4 |
| A6 | 2.5% NC + 97.5% CS | 264.3 |
| A7 | 3.0% NC + 97.0% CS | 268.0 |
| A8 | 3.5% NC + 96.5% CS | 265.6 |
| A9 | 4.0% NC + 96.0% CS | 263.3 |

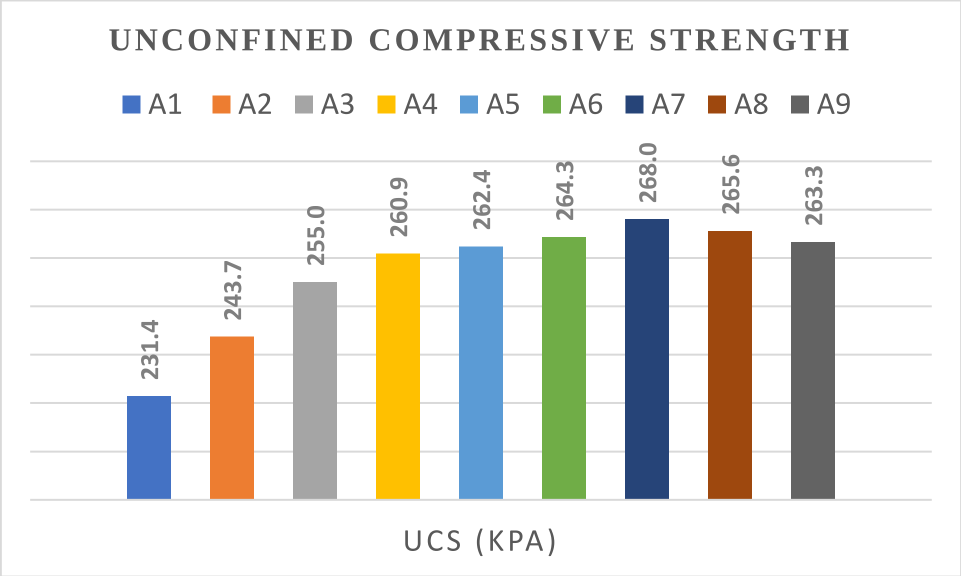


Figure 8 Compressive strength of nanoclay mixture

### 4.4 Effect of Nanoclay on Atterberg Limit Parameters:

Table 6 and Figure 9 presents the changes observed in the Atterberg limit parameters, namely the Plastic Limit (PL), Liquid Limit (LL), and Plasticity Index (PI). Upon the addition of 3% nanoclay (A7) to the clayey soil, the LL and PL increased by 22.96 % and 72.69 %, respectively. In contrast, the PI decreased by about 36.97 %, suggesting an enhancement in soil behavior. This reduction in PI indicates improved soil workability, implying that nanoclay particles are beneficial for geotechnical applications such as soil liners and fill caps Taha MR (2009).

Table 6 Result of compressive strength soft soil mixed with nanoclay

| Abbreviation | Liquid Limit (%) | Plastic Limit (%) | Plasticity Index (%) |
|---|---|---|---|
| A1 | 45.3 | 22.7 | 22.6 |
| A2 | 47.9 | 27.1 | 20.8 |
| A3 | 51.0 | 31.3 | 19.7 |
| A4 | 53.2 | 35.0 | 18.2 |
| A5 | 54.1 | 36.8 | 17.3 |
| A6 | 55.5 | 38.4 | 17.1 |
| A7 | 55.7 | 39.2 | 16.5 |
| A8 | 56.8 | 40.3 | 16.53 |
| A9 | 57.1 | 40.5 | 16.6 |

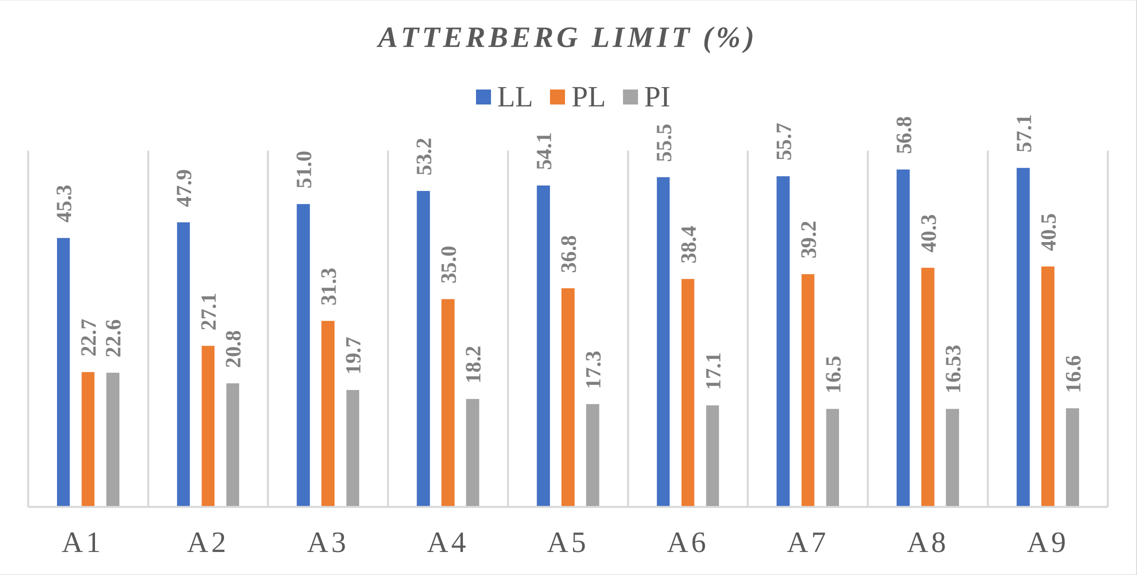
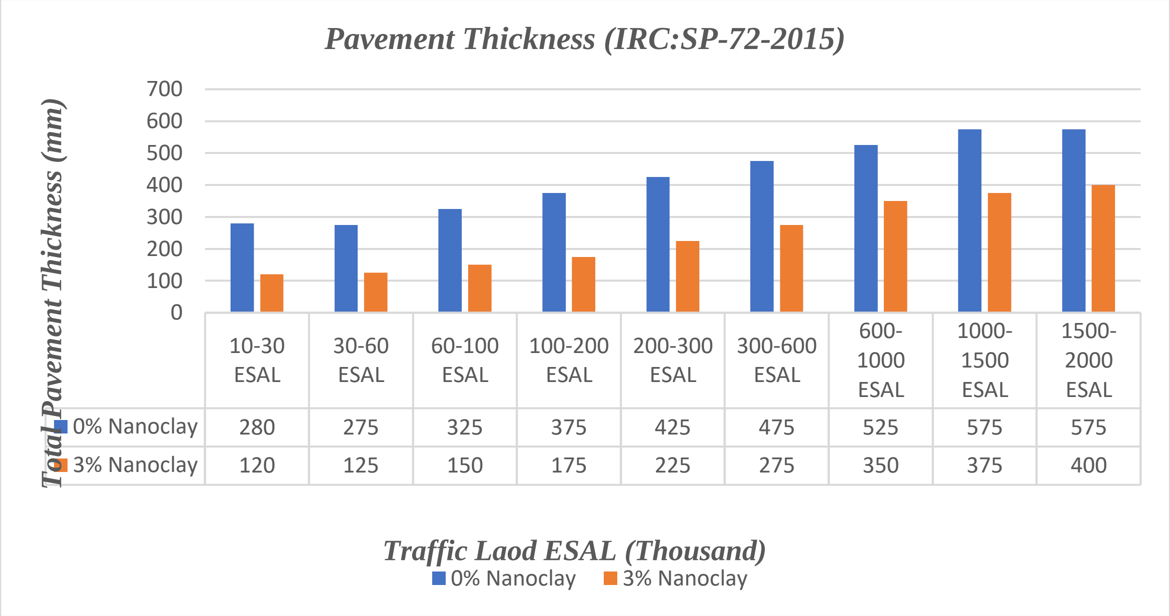


Figure 9 Variation of Atterberg limit with nanoclay mixture

### 4.5 Pavement Design Based on Soaked CBR Values and Cost Optimization:

The design of flexible pavements for rural roads IRC SP 72-2015. in this study was carried out based on soaked California Bearing Ratio (CBR) values. Using these CBR values, the total pavement thickness required was calculated for a range of traffic loads, from 10,000 to 2,000,000 Equivalent Single Axle Loads (ESALs) Figure 10. The comparative analysis, depicted in Figure 11 reveals that incorporating 3% nanoclay into the soil significantly reduced the required pavement thickness by 26% to 46%. This reduction in thickness implies lower material consumption and decreased transportation needs, contributing to a reduction in carbon emissions associated with pavement construction.

To assess the economic viability of the nanoclay, a cost comparison of three pavement types Pavement A (untreated soil mixture) and Pavement B (3% nanoclay-modified soil), was conducted. The analysis assumed a traffic load of 600-1,000 ESALs over a 1 km road section with a 7 meter-wide carriageway.



| | 10-30 ESAL | 30-60 ESAL | 60-100 ESAL | 100-200 ESAL | 200-300 ESAL | 300-600 ESAL | 600-1000 ESAL | 1000-1500 ESAL | 1500-2000 ESAL |
|---|---|---|---|---|---|---|---|---|---|
| 0% Nanoclay | 280 | 275 | 325 | 375 | 425 | 475 | 525 | 575 | 575 |
| 3% Nanoclay | 120 | 125 | 150 | 175 | 225 | 275 | 350 | 375 | 400 |

Figure 10 Total required pavement thickness (mm) at different traffic loads (ESAL)

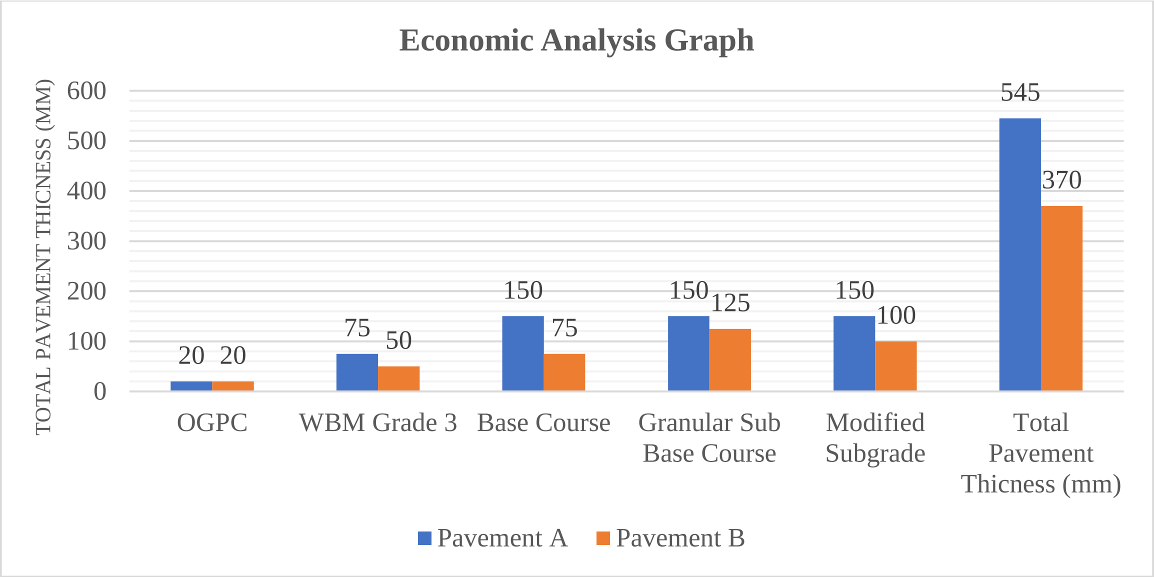


Figure 11 Compositions for different types of pavement based upon CBR

The required material volume for each design thickness was calculated and multiplied by standard rates from the Central Public Works Department (CPWD 2019). Pricing for the nanoclay and its application cost was sourced from an authorized Indian distributor Dheeraj et al. (2019). Only direct costs material, machinery, transportation, and labour were included in the cost estimation. As illustrated in Figure 11, Pavement B, which utilized the 3% nanoclay, showed a significant cost saving of approximately ₹33.47 lakhs (INR) per kilometer compared to Pavement A. This results underline that nanoclay modified soil not only enhances the geotechnical performance and environmental sustainability of the pavement but also contributes to a substantial reduction in construction costs.

## 5. Conclusions

This laboratory based study aimed to evaluate the effectiveness of the nanoclay as a chemical stabilizer for enhancing soil subgrade properties. The investigation focused on compaction characteristics, Atterberg limit, and mechanical strength through CBR and UCS tests, and microstructural analysis using XRD and SEM techniques. Based on the experimental results, the following conclusions were drawn:

1. The XRD analysis of clayey soil-nanoclay mixtures revealed a noticeable shift in the characteristic peak from $2\theta = 5.90°$ to $2\theta = 3.30°$ for samples with 0.5% and 3% nanoclay content. This reduction in peak intensity and the corresponding increase in interlayer spacing indicate the formation of intercalated and agglomerated nanostructures. These findings suggest partial exfoliation of silicate layers, which contributes to improved soil structure and performance.
2. The SEM analysis of clayey soil blended with 3% nanoclay demonstrated a significant enhancement in surface morphology, indicating increased surface area available for particle interaction. This led to improved inter-particle bonding and the formation of a more uniform and denser microstructure. The observed microstructural refinement is directly linked to enhanced engineering properties such as higher strength, smoother texture, and improved load distribution capability.
3. The addition of nanoclay significantly reduce the plasticity index about 36.97 %, and improved both geotechnical and mechanical strength parameters of the cement-modified soil mixture.

4. The UCS test confirmed that the addition of nanoclay improved soil strength of the sample. Notably, a 3% nanoclay content showed the most significant improvement, thus identifying 3% as the optimum dosage for soil stabilization.
5. The pavement designed with 3% nanoclay modified soil demonstrated a substantial cost saving of approximately ₹33.47 lakhs per kilometer in comparison to conventional untreated soil based pavement. This finding highlights the dual advantage of using nanoclay: it not only enhances the geotechnical and structural performance of the subgrade but also promotes environmental sustainability by optimizing material usage and reducing carbon emissions. The significant reduction in construction cost underscores the economic viability of nanoclay as an innovative solution for modern pavement design.

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