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# Soil Stabilization with Nanomaterial: Nanoclay

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**Abstract**

Soil consists of several particles of different sizes varied from 4.75cm to 1nm; more voids spaces developed between soil particles depend on their specific sizes. If void spaces elevated in the soil structure, soil acted like high permeable, more settlement, less stability, enhanced the plasticity index, impact on shear strength, compaction, and consolidation characteristics. The regaining of the structure against all the properties introduced a new technology for stabilization: nanotechnology. Nanotechnology is an innovative method that describes nanomaterials additional to weak natural soil for filling the voids in Nano level i. e 1nm to 100nm and will improve all geotechnical properties. The main advantage of this innovative method is using nanomaterials; the size nanomaterials are lying between 15 to 80nm filled with any size of void space. In the present study, aimed to be improved the plasticity index, specific gravity, compaction, shear strength (Unconfined Compressive Strength-UCS), and permeability characteristics by adding nanomaterial: Nanoclay. Stabilization of soil with Nanoclay proven excellent results and improved all geotechnical properties such as index and engineering properties. Determine the optimum dosage of the Nanoclay effect on the soil and responses on specific gravity, index, and engineering properties of soil. At the optimum dosage of Nanoclay proved maximum escaped all voids and filled with Nanoclay particles. The stabilization is useful for all embankments related to civil, geotechnical, transported, and slope stability also.

*Keywords: Nanoclay, Nanomaterial, Nanotechnology, Index properties, and Engineering properties.*

## *1. Introduction*

Nowadays, the role of Nanomaterial agents is increasing in various applications; it is an essential requirement to improve the soft clay soils before make a road pavement or embankment or design a foundation for any infrastructure [1]. Even various conventional ground improvement techniques are available; the Nanomaterial treated soils proved to make the treatment cheaper due to the addition of a very low dosage of Nanomaterial agents. This Nanomaterial also acts as a water barrier so that the strength becomes constant for the long-term. Therefore present study attempt to examine the permeability and compressibility characteristics of Nano-material treated soils that directly dictate the strength of treated soil. The size of soil particles varied from 90mm to 100nm and behaved as weak against strength, settlement, and stability because these sizes developed pores at the average level to Nano level. It exhibited more swelling and shrinkage characteristics [2]. Soil consists of gravel, sand, silt, and clay, in that the specific size of clay particles much more than other soil types. The structure of clay studied from SEM (scanning electron microscope) analysis to recognize the measurement and morphology of the soil particles [3, 4].

The regaining of these properties, clay stabilized with additives like cement, lime, fly ash, and silica fume. The size of these materials is micro, and the pores filled in micro-level and lightly impact on Plasticity Index, specific gravity, compaction, shear strength, and permeability characteristics [5, 6]. The improved performance of soil not sufficient of these additives, and only filled in micro level, that's why introduced new technology: nanotechnology, the pores of soil-filled in Nano-level, and acted as more compacted, impacted on Plasticity Index, specific gravity, compaction, shear strength, and permeability characteristics [7-9].

In nanotechnology, the nanomaterials added to local available weakly soil improved all geotechnical properties. Some of the Nanomaterials: Terrasil, Nano-silica, and Nanoclay [10-13]. The nanomaterials have more advantages in point of scientific, environmental, economic, and improved quality of the product. Among all nanomaterials, Nanoclay proved excellent results on the index and engineering properties of soils. The Nano clay effected on the plasticity index and improved the liquid limit by adding very little of the percentages of Nanoclay to soil [14]. Nanoclay used to improve index and engineering properties of soils, mainly UCS, California bearing ratio test (CBR), and Permeability characteristics with very low dosages. The dosages of Nanoclay are varying from 0.5 to 5% of the dry weight of soil [15-19]. The main objective enhanced Plasticity Index, specific gravity, compaction, shear strength, and permeability characteristics by adding nanomaterial: Nanoclay. Stabilization of soil with Nano clay proven excellent results and improved all geotechnical properties such as index and engineering properties.

## 2. Methodology

Improvement of consistency limits, specific gravity, and permeability characteristics of soft soil with nanomaterial, Figure 1 explains the methodology of improvement of geotechnical properties of soft soil with nanomaterial and all the process of improvement of soil with Nanoclay.

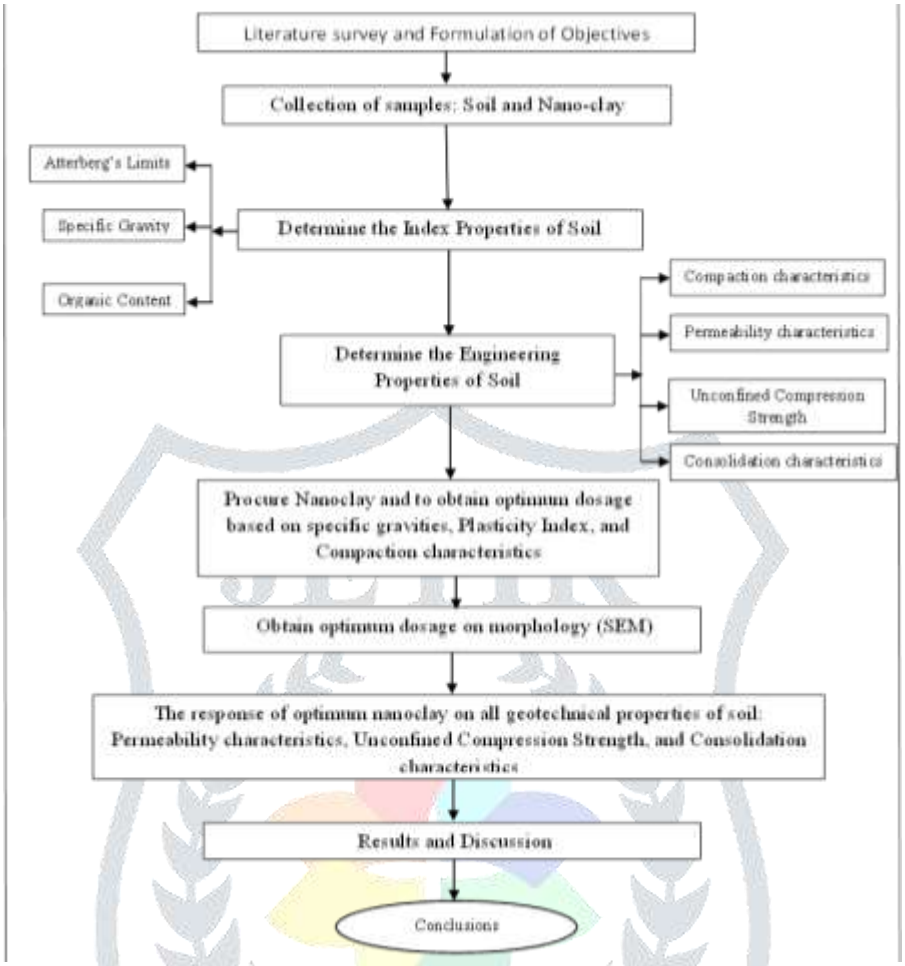


Fig. 1 The process of improvement of soil with Nanoclay

## 3. Experimental Tests

### 3.1 Material

A clay soil collected from lankapalli, Krishna Dist., Andhra Pradesh state and black cotton soil distributed throughout the area and construction of any civil and agricultural structures get very problematic and need to stabilize with nanomaterials. The disturbed had collected at the height of 1m below ground surface, the soil sample was oven dry at 110$^{o}$C, and air-dried the sample, compacted and separation the soil based on grain sizes. Table 1 indicates the index properties of soil. Field dry density of soil is 16.6kN/m$^2$ with natural moisture content is 15.70% at the height of 1m below the ground surface; these values had taken before soil collected and determine all geotechnical properties of the soil according to IS:2720-1965.

Table 1 Index properties of soil

| S. No | Property | Values |
|---|---|---|
| 1 | Specific Gravity(G) | 2.125 |
| 2 | Consistency limits<br>Liquid limit (%)<br>Plastic limit (%)<br>Plasticity Index ($I_P$) (%) | <br>28.18<br>12<br>16.28 |
| 3 | Shrinkage limit (%) | 9 |

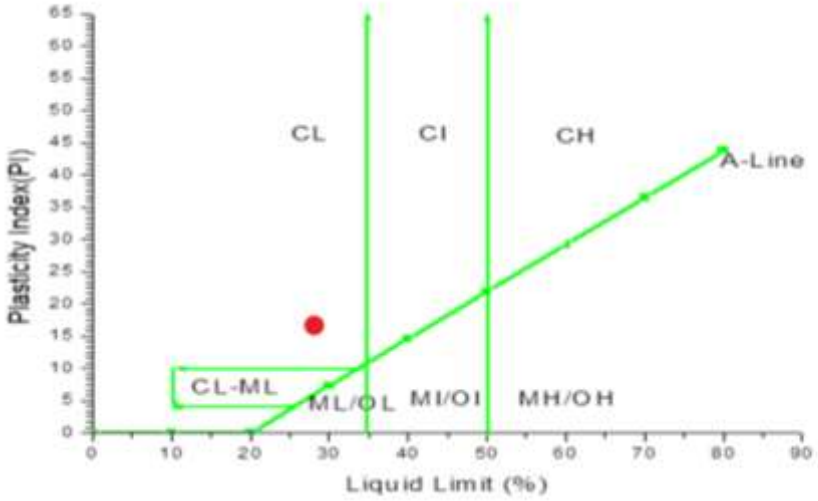


Fig. 2 A-line chart for the clay soil

Based on consistency limits of clay soil, soil classified as (IS Grain size analysis –A-line) Low Compressible Clay- CL, Figure 2 indicated classification of soil; this type of soils created very problematic loading, unloading, or absence of applying load. It contains more voids that lead to more settlement, compressibility, and low shear strength, mainly effect on roads, embankments, or any structural slopes. Table 2 contains the engineering properties of soil.

Table 2 Engineering properties of soil

| S. No | Property | Values |
|---|---|---|
| 1 | IS Light compaction | |
| | (a) Maximum Dry Density MDD (g/cc) | 1.62 |
| | (b) Optimum Moisture Content OMC (%) | 18.18 |
| 2 | Unconfined Compression Strength (UCS) ($kN/m^2$) | 36 |
| 3 | Co-efficient of permeability (cm/s) | $2.4 \times 10^{-6}$ |
| 4 | Consolidation Test: | |
| | Compression index-Cc | 0.149 |
| | Co-efficient of compressibility $a_v$ ($kg/cm^2$)-1 | 0.42 |
| | Co-efficient of volume change $m_v$($kg/cm^2$)-1 | 0.29 |
| | Co-efficient of consolidation $c_v$ ($cm^2$/min) | 0.022 |
| | Final settlement (mm) | 4.2 |

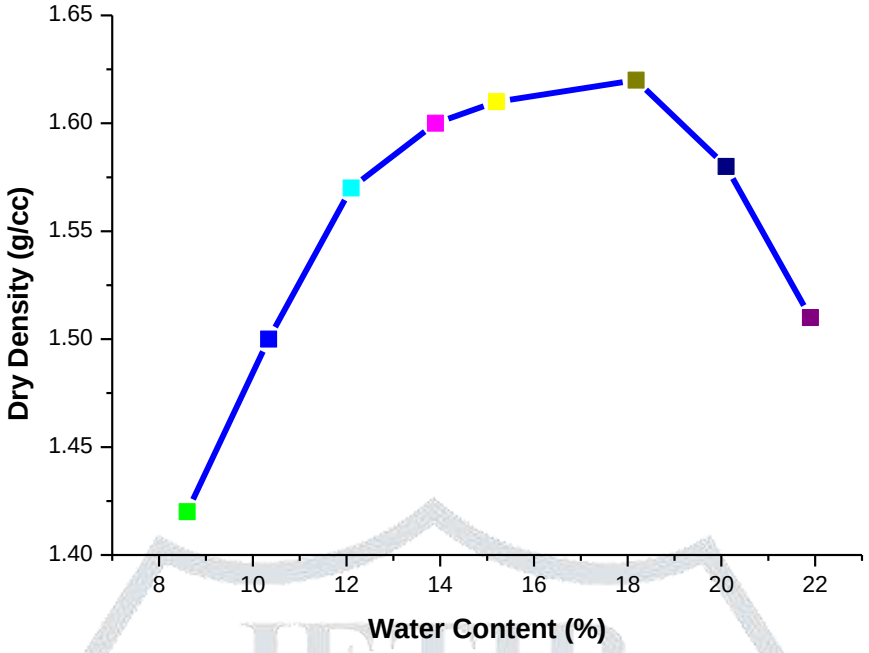


Fig. 3 Compaction curve for the clay soil

Based on engineering properties: soil classified as very soft-clay depend UCS is 36kN/m$^2$, the type of soils created very problematic loading, unloading, or absence of applying load. Figures 3 indicated the results from the compaction test in terms of MDD and OMC; the dry densities increased with moisture contents at one point after it reduced, that point called maximum dry density.

### 3.2 Nano-clay

The nanomaterials stabilized geotechnical properties of weak soil, Nanoclay used as a nanomaterial. The specifications, finite elements, and SEM of Nanoclay represent the following table 3 and figures 4 illustrated the details of the specification, chemical compounds, SEM image, and FE images. The Nano clay procured from Nano Research Elements, India. The physical and major oxides of the nanoclay described in table 3.

Table 3 Specification and chemical compounds of Nanoclay

| S. No | Item Description | Values |
|---|---|---|
| 1 | Formula | $Na_{0.2}Ca_{0.1}Al_2Si_4O_{10}(OH)_2(H_2O)_{10}$ |
| 2 | Molecular Weight | 549.07231g/mol |
| 3 | APS | <100nm |
| 4 | Color & Form | Light cream/off white & Powder |
| 5 | Purity | 99.9% |
| 6 | Density | 2~3g/cm$^3$ |
| 7 | Melting Point | 1750°C |
| 8 | Boiling Point | NA |
| 9 | $SiO_2$ (%) | 43.69 |
| 10 | $Al_2O_3$ (%) | 18.07 |
| 11 | $Na_2O$ (%) | 1.12 |
| 12 | CaO (%) | 1.02 |
| 13 | $H_2O$ (%) | 36.09 |
| 14 | Others | 800ppm |

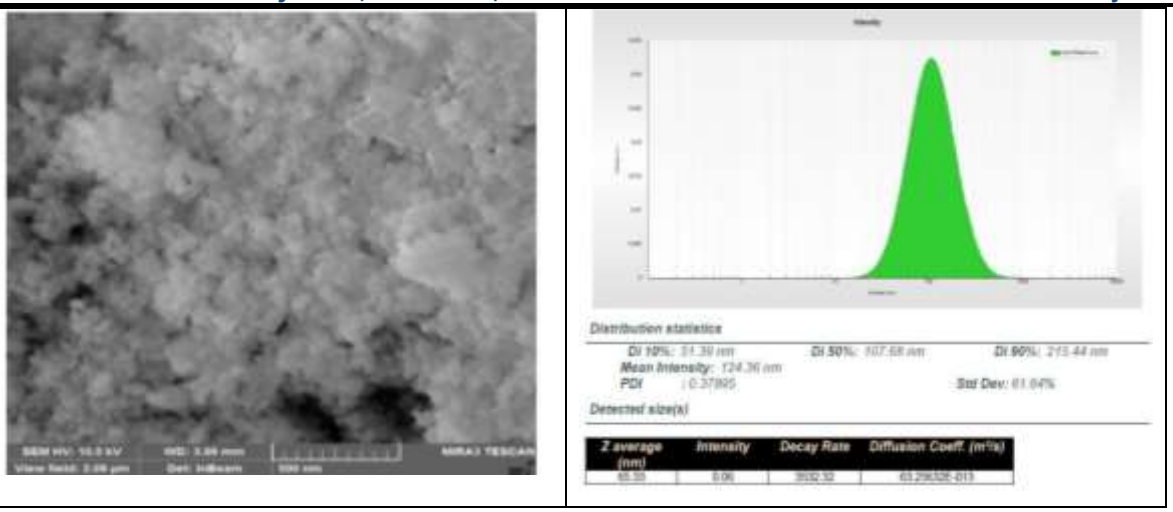


Fig. 4 SEM and FE images of Nanoclay

**4. The Optimum dosage of Nanoclay with weak soil**

Different percentages, such as 0.05% to 5% of Nanoclay added to weak soil, find the optimum dosages depend on i) Specific gravity, ii) Plasticity Index, and iii) Compaction characteristics. For that, soil prepares with the percentages of Nanoclay, such as 0.05% to 5% of the dry weight of soil.

**4.1 Soil Sample preparation**

Soil samples prepared to determine the improvement of specific gravity, consistency limits, and compaction and other Index and Engineering properties of soft-clay, but geotechnical properties divided into two types: Index and Engineering properties of soft-clay. Soil samples prepared according to the requirement of these two properties.

Two sections of analysis: a) Soil preparation for index properties-Specific gravity, Plasticity Index, and b) Soil preparation for engineering properties-Compaction characteristics.

Samples preparation for both index and engineering properties: the soft-clay soil has mixed with optimum moisture content, maximum dry density, and the percentages of Nanoclay such as 0.05, 0.10, 0.15, 0.25, 0.5, 0.75, 1, 2, 3, 4, and 5% of the dry weight of soil. The samples kept in final packing because of avoiding water evaporation. Figure 5 indicates the prepared soil samples for testing index and engineering properties.


Fig. 5 Soil specimens for index and engineering properties

### 4.2 Specific Gravity

These prepared samples tested according to IS: 2720-1965 and respected specific gravities of 0.05, 0.10, 0.15, 0.25, 0.5, 0.75, 1, 2, 3, 4, and 5% of dry weight of soil. Table 4 and figure 6 contain the results of specific gravities on mixed soil with Nanoclay.

Table 4 Specific gravities of soil mixed with Nanoclay

| S. No | Percentages of Nanoclay (%) | Specific Gravities |
|---|---|---|
| 1 | 0.05 | 2.266 |
| 2 | 0.1 | 2.302 |
| 3 | 0.15 | 2.365 |
| 4 | 0.25 | 2.186 |
| 5 | 0.5 | 1.974 |
| 6 | 0.75 | 1.807 |
| 7 | 1 | 1.701 |
| 8 | 2 | 1.64 |
| 9 | 3 | 1.53 |
| 10 | 4 | 1.46 |
| 11 | 5 | 1.35 |

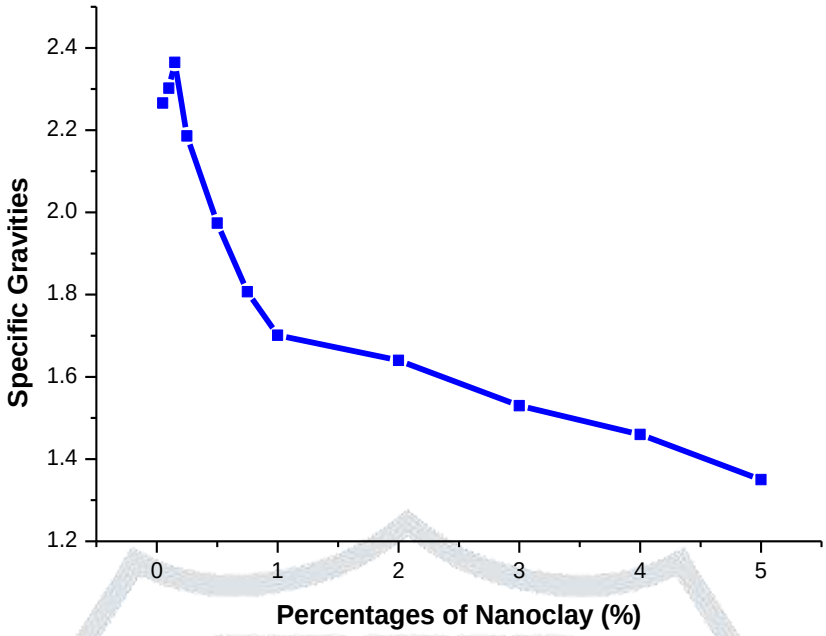


Fig. 6 The response of specific gravities on percentages of Nanoclay

Initially, the specific gravity of natural soil is 2.125 after adding the percentages of nanoclay, and the specific gravity increased from 2.125 to 2.365 in the percentages of 0.15% among all percentages; remaining specific gravities have decreased, so the maximum specific gravity obtained at 0.15% of nanoclay, the results concluded that the percentage fixed as the optimum dosage of Nanoclay to the soil.

### 4.3 Plasticity Index

These prepared samples tested according to IS: 2720-1965 and respected Plasticity Indexes of 0.05, 0.10, 0.15, 0.25, 0.5, 0.75, and 1% of the dry weight of soil. The percentages have reduced from the results of the specific gravity test. Table 5 contains the results of Atterberg's limits on mixed Nanoclay. The liquid and plastic limits changed with the addition of Nanoclay and also influenced grain size distribution. Plasticity index maximum reduced at 0.15% of Nanoclay mixed with the soil. Figure 7 represents the response of the Plasticity Index with percentages of Nanoclay.

Table 5 Atterberg's limits results of the soil with Nanoclay

| **Percentages of Nanoclay** | **0.05** | **0.1** | **0.15** | **0.25** | **0.5** | **0.75** | **1** |
|---|---|---|---|---|---|---|---|
| Liquid limit (%) | 35 | 37 | 38.5 | 39.5 | 44.5 | 54 | 56 |
| Plastic limit (%) | 14 | 17 | 18 | 16 | 16.5 | 23 | 24 |
| Plasticity Index (%) | 21 | 20 | 19.5 | 23.5 | 28 | 31 | 32 |

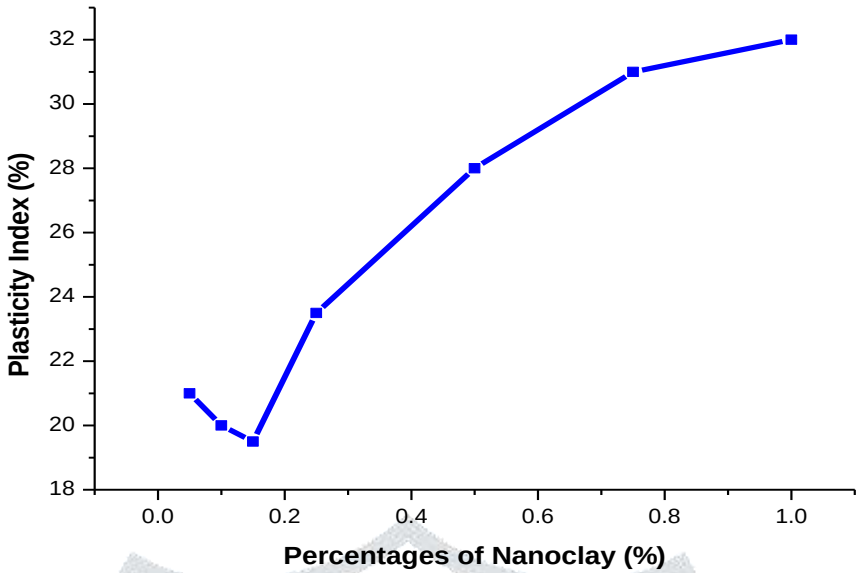


Fig. 7 The response of the plasticity index on percentages of Nanoclay

**4.4 Compaction Characteristics**

These prepared samples tested according to IS: 2720-1965 and respected compaction Characteristics of 0.05, 0.10, 0.15, 0.25, and 0.5% of the dry weight of soil. Table 6 contains the results of compaction characteristics on mixed Nanoclay. The Maximum dry densities increased the maximum 1.81kN/m$^2$ at the percentages of 0.15% of Nanoclay with the soil and influence grain size distribution. Figure 8 represents the response of the compaction Characteristics with percentages of Nanoclay.

Table 6 The response of the compaction Characteristics with percentages of Nanoclay

| **Percentages of Nanoclay** | **0.05** | **0.1** | **0.15** | **0.25** | **0.5** |
|---|---|---|---|---|---|
| MDD (g/cc) | 1.76 | 1.78 | 1.81 | 1.785 | 1.77 |
| OMC (%) | 16 | 15 | 13.5 | 13 | 12 |

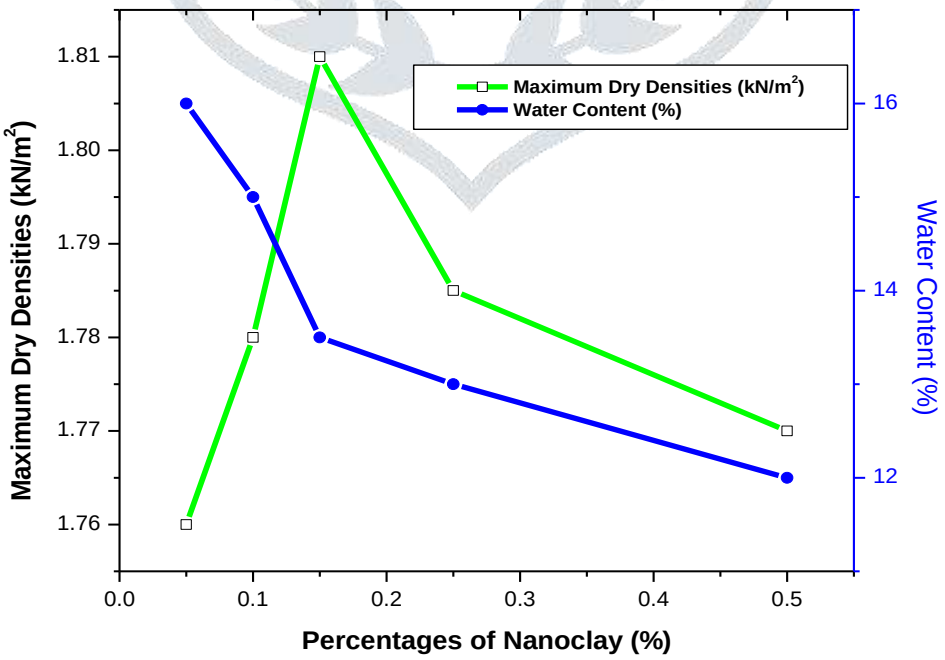


Fig. 8 The response of compaction characteristics on percentages of Nanoclay

**Concluding from Specific Gravity, Plasticity Index, and Compaction Characteristics**

From these three tests, among all the percentages 0.05, 0.10, 0.15, 0.25, 0.5, 0.75, 1, 2, 3, 4, and 5% of dry weight of soil, at the percentage 0.15 of Nanoclay treated maximum specific gravity (increased from 2.125 to 2.365), reduced plasticity index (from 21% to 19.5%), and significant maximum dry density (from 1.62 to 1.81kN/$m^2$). Every changed at the percentage of 0.15% of Nanoclay so that the optimum dosage of Nanoclay to the soil.

## 5. Results and Discussion

### 5.1 The responses of soil mixed Nanoclay on Permeability characteristics

Samples preparation for Permeability characteristics: the soft-clay soil has mixed with optimum moisture content, maximum dry density, and optimum dosages of Nanoclay with curing periods of 1, 3, 9, and 18 days. The samples kept in final packing because of avoiding water evaporation.

The prepared samples tested according to IS: 2720-1965 and respected Permeability characteristics: the soft-clay soil has mixed with optimum moisture content, maximum dry density, and optimum dosages of Nanoclay with curing periods of 1, 3, 9, and 18 days. Table 7 contains the results of Permeability characteristics on soil mixed with Nanoclay.

Table 7 Test results from Permeability test

| **Curing Periods (Days)** | **0** | **1** | **3** | **9** | **18** |
|---|---|---|---|---|---|
| Permeability characteristics (cm/s) | $2.4 \times 10^{-6}$ | Nil | Nil | Nil | Nil |

From this test noted: Permeability characteristics completely nil. Due to adding of optimum dosage Nanoclay, the void spaces filled with nanomaterials at the Nano level, so soil acted as entirely impermeable.

### 5.2 Unconfined Compression Strength test

Samples preparation for Unconfined Compression Strength characteristics: the soft-clay soil has mixed with optimum moisture content, maximum dry density, and optimum dosages of Nanoclay with curing periods of 1, 3, 9, and 18 days. The samples kept in final packing because of avoiding water evaporation.

They prepare samples tested according to IS: 2720-1965 and respected Unconfined Compression Strength characteristics: the soft-clay soil has mixed with optimum moisture content, maximum dry density, and optimum dosages of Nanoclay with curing periods of 1, 3, 9, and 18 days. Table 8 and figure 9 contain the result of Unconfined Compression Strength characteristics on soil mixed with Nanoclay.

Table 8 Test results for UCS test

| **Curing Periods (Days)** | **0** | **1** | **3** | **9** | **18** |
|---|---|---|---|---|---|
| Unconfined Compression Strength (UCS) (kN/$m^2$) | 36 | 65 | 72 | 80 | 128 |

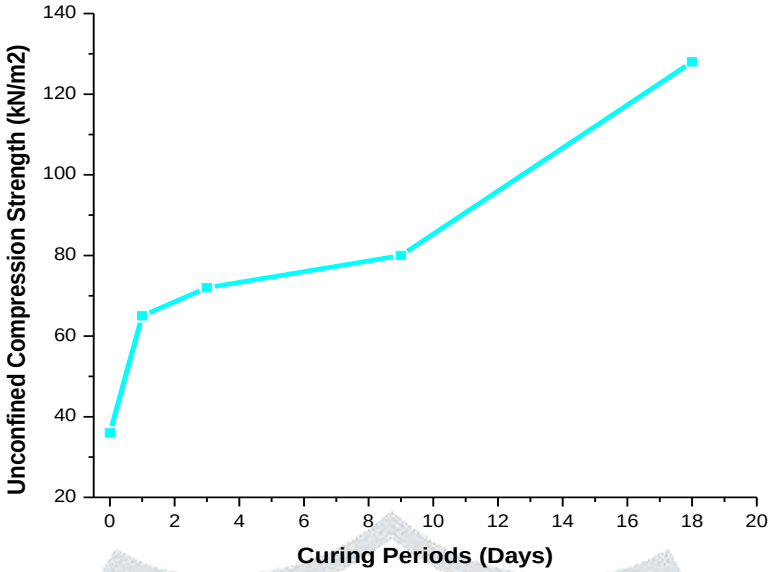


Fig. 9 The response of UCS on optimum percentages of Nanoclay

From this test noted: Unconfined Compression Strength characteristics increased from 36 to 128kN/m$^2$ at 0.15% of Nanoclay in 18 days curing periods-Porous space filled with Nanoclay particles and improved compressive strength of the soil.

### 5.3 Consolidation characteristics

Samples preparation for Consolidation characteristics: the soft-clay soil has mixed with optimum moisture content, maximum dry density, and optimum dosages of Nanoclay with curing periods of 1, 3, 9, and 18 days. The samples kept in final packing because of avoiding water evaporation.

They prepare samples tested according to IS: 2720-1965 and respected Consolidation characteristics: the soft-clay soil has mixed with optimum moisture content, maximum dry density, and optimum dosages of Nanoclay with curing periods of 1, 3, 9, and 18 days. Table 9 and figure 10 contain the results of Consolidation characteristics on soil mixed with Nanoclay.

Table 9 Test results of consolidation at the optimum dosage of Nanoclay

| **Curing Periods (Days)** | **0** | **1** | **3** | **9** | **18** |
|---|---|---|---|---|---|
| Final Settlement $\Delta H$ or $S_f$ (mm) | 4.2 | 3.7 | 3.01 | 2.5 | 1.1 |
| Co-efficient of consolidation $C_V$ (cm$^2$/min) | 0.022 | 0.052 | 0.083 | 0.12 | 0.23 |

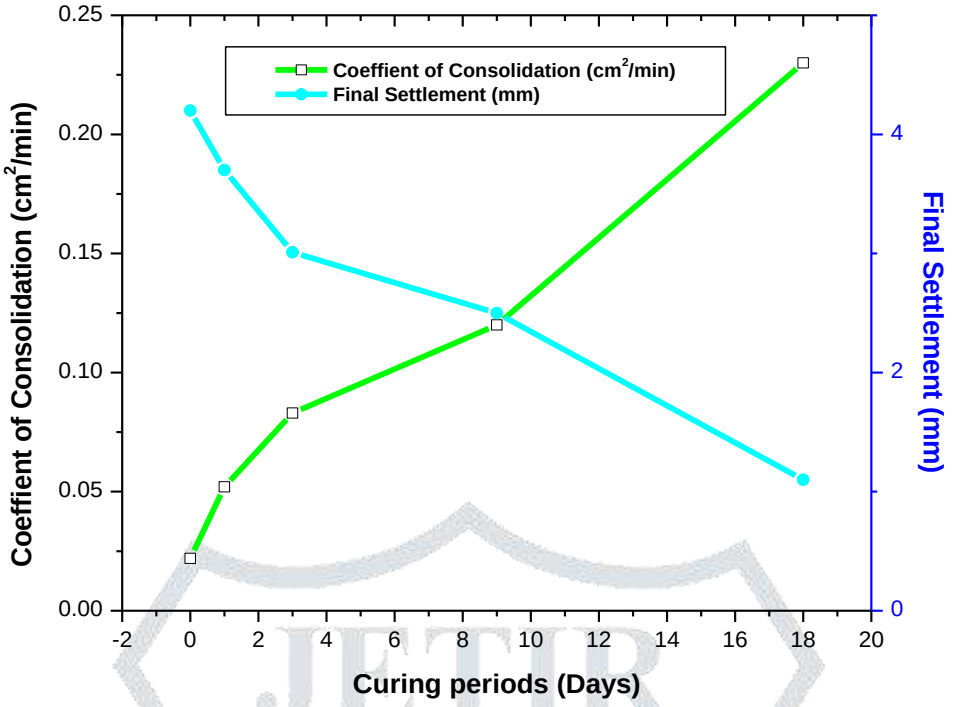


Fig. 10 The response of co-efficient of consolidation and Settlements values at the optimum dosage of Nanoclay

From this test noted: The co-efficient of consolidation (Degree of consolidation) characteristics increased from 0.022 to 0.23cm$^2$/min at the optimum dosage of Nano clay (0.15%) in the 18 days curing period. At the same time, the final settlement decreased from 4.2 to 1.1mm; it indicated that the settlements controlled, and it useful for all embankments related to civil, geotechnical, transported, and slope stability also. Figure 10 explained the response of the co-efficient of consolidation and Settlements values with the Nanoclay. Due to the void spaces filled with Nanoclay and improved consolidation characteristics.

**Conclusions**

The experimental work on improved soft-clay with Nanoclay, index, and engineering properties of soft-clay, and the results concluded as follows:

1. Soil classified as Low Compressible Clay (CL) depends on Atterberg's limits. The soil has MDD, and OMC is 1.62 g/cc and 18.18%, respectively.
2. The coefficient of permeability is about 2.4 × $10^{-6}$ cm/sec, and UCS of clay soil found to 36kN/m$^2$. The coefficient of consolidation found to 0.023cm$^2$/min, and the final consolidation settlement is about 4.2mm. So it is clear that the soil is High compressible clay.
3. The soft-clay soil has mixed with optimum moisture content, maximum dry density, and the percentages of Nanoclay such as 0.05, 0.10, 0.15, 0.25, 0.5, 0.75, 1, 2, 3, 4, and 5% of the dry weight of soil.
4. The specific gravity increased in the percentages of 0.15% among all percentages; remaining specific gravities have decreased so that 0.15% is the optimum dosage of Nanoclay to the soil.
5. The liquid and plastic limits changed with the addition of Nanoclay and also influenced grain size distribution. Plasticity index maximum reduced at 0.15% of Nanoclay mixed with the soil.
6. The Maximum dry densities increased the maximum 1.81kN/m$^2$ at the percentages of 0.15% of Nanoclay with the soil and influence grain size distribution.
7. Among all the percentages 0.05, 0.10, 0.15, 0.25, 0.5, 0.75, 1, 2, 3, 4, and 5% of the dry weight of soil, at the percentage 0.15 of Nanoclay treated maximum specific gravity (increased from 2.125 to 2.365), reduced plasticity index (from 21% to 19.5%), and significant maximum dry density (from 1.62 to 1.81kN/m$^2$). Every changed at the percentage of 0.15% of Nanoclay so that the optimum dosage of Nanoclay to the soil.
8. Permeability characteristics were utterly nil: the optimum dosage Nanoclay, the total pores filled with nanomaterials, soil act as entirely impermeable.
9. Unconfined Compression Strength characteristics increased from 36 to 128kN/m$^2$ at 0.15% of Nanoclay in 18 days curing periods-Porous space filled with Nanoclay particles and improved compressive strength of the soil.
10. The co-efficient of consolidation characteristics increased at the optimum dosage of Nanoclay (0.15%) in the 18 curing period. At the same time, the Final settlement decreased from 4.2 to 1.1mm.

References

[1] T.W. Lamb, R.V. Whitman, Soil Mechanics, John Wiley & Sons Publishing, 1969
[2] G. Zhang, "Soil nanoparticles and their influence on engineering properties of soils." Advanced in measurement and modelling of soil behavior, ASCE 2007.
[3] M.R. Yalamanchili, S. Veeramasuneni, M.A.D. Azevedo, J.D. Miller, "Use of atomic force microscopy in particle science and technology research," Colloids and Surfaces a Physicochemical and Engineering Aspects 133 (1998) 77–88.
[4] G. Kollensperger, G. Friedbacher, A. Krammer, M. Grasserbauer, "Application of atomic force microscopy to particle sizing," Journal of Analytical & Bioanalytical Chemistry, 363 (4) (1999) 323–332.
[5] R. Feynman, there is plenty of room at the bottom, Engineering and Science (California Institute of Technology) 23(1960) 22–36.
[6] R. Booker, E. Boysen, Nanotechnology for Dummies, Wiley Publishing, (2005) 384.
[7] R Zhu., S Lau, "A high-resolution TEM investigation of nanoparticles in soils," Journal of Molecular Environmental Soil Science at the Interfaces in the Earth Critical Zone, (2010) 282–284.
[8] K.K. Jha, "An Energy Based Nano mechanical Properties Evaluation Method for Cementitious Materials," Ph.D. Dissertation, Florida International University, Miami, FL, USA, 2012.
[9] A. Mohamadzadeh Sani, M. Arabani, A.K. Haghi, R.J. Chenari, "Effect of Nanoclay additive on the geotechnical properties of silty sands," Proc. of 4th International Conference on Geotechnical Engineering and Soil Mechanics, Tehran, 2–3 November 2010, (in Persian).
[10] M Arabani., A.K Haghi., A. Mohamadzadeh Sani, N. Kambozia, "Use of Nanoclay for improvement the microstructure and mechanical properties of soil stabilized by cement," in: Proc. of the 4th International Conference on Nanostructures (ICNS4), 12–14 March, Kish Island, Iran, 2012.
[11] N. Khalid, M.F. Arshad, M. Mukri, K. Mohamad, F. Kamarudin, "Influence of Nano-Soil Particles in Soft Soil Stabilization," 20 (2015) 731-738.
[12] H.L Lou., D.H. Hsiao, C.K. Lin, "Cohesive soil stabilized using sewage sludge ash/cement and nano aluminum oxide," International Journal of Transportation Science and Technology 1(1) (2012) 83–100.
[13] M. Nikookar, M. Bahari, H. Nikookar, M. Arabani, "the strength characteristics of silty soil stabilized using Nanoclay," Proc. of 7th Symposium on Advances in Science & Technology (7thsastech), 7–8 March (2013), Bandar-Abbas, Iran, 2013.
[14] Z.H. Majeed, M.R. Taha, "Effect of nanomaterial treatment on geotechnical properties of a Penang soft soil," Asian Scientific Research 2(11) (2012) 587–592.
[15] M. Ghazavi, M. Bolhasani, "Unconfined compression strength of clay improvement with lime and nano-silica," Proc. Of 6th International Congress on Environmental Geotechnics, New Delhi, India, 8–10 November (2010) 1490–1495.
[16] S.A.R. Seyedi Gelsefidi, J. Mamaghanian, "Stabilization of weak low plasticity clay soil using nanomaterial," in: Proc. of 5th International Young Geotechnical Engineers, (2013) 134–137.
[17] N. Ghasabkolaei, A. Janalizadeh, M. Jahanshahi, N. Roshan, S.E. Ghassemi, "Physical and geotechnical properties of cementtreated clayey soil using silica nanoparticles: an experimental study," The European Physical Journal Plus, 131 (5), 1–11.
[18] S.H. Bahmani, B.B.K. Huat, A. Asadi, N. Farzadnia, "Stabilization of residual soil using SiO2 nanoparticles and cement," Construction and Building Materials (2014) 350–359.
[19] M.R. Taha, "Geotechnical properties of soil–ball milled soil mixtures," in: Proc. 3rd Symp Nanotechnology in Construction, Springer-Verlag, (2009) 377–382.