Experimental Investigation on Static and Dynamic Characterization of Clayey Soil Treated with Nano-SiO_2 and Fly Ash for Geotechnical Applications

Thesis submitted in partial fulfillment

for the Award of Degree

Doctor of Philosophy

by

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19061017 ***June 2025***

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It is certified that the work contained in the thesis titled "**Experimental Investigation on Static and Dynamic Characterization of Clayey Soil Treated with Nano-SiO_2 and Fly Ash for Geotechnical Applications**" by "**Ms. Jayanti Munda**" has been carried out under my supervision and that this work has not been submitted elsewhere for a degree.

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ABSTRACT

The clay deposit is the biggest challenge to the safe and cost-effective design of geotechnical projects and infrastructure. Because of its undesirable properties, which lead to underlying issues in a variety of construction projects, this type of soil is typically considered troublesome in the field of geotechnical engineering. This type of soil usually has a high initial water content, a high void ratio, poor strength, low permeability, and high compressibility. Soil stabilization is a common and affordable method in geotechnical engineering to improve the properties of the problematic soil. Among various techniques, one way to improve the soil is to use traditional binders such as cement or lime. Although the majority of applications have demonstrated the effectiveness of calcium-based additives, their main drawback has been extensively studied in the past and has primarily been related to the environmental impact associated with their production. These traditional stabilizing materials can significantly enhance the engineering properties of soil structures, despite the fact that there are still some significant drawbacks and environmental concerns. Among the environmental problems caused by excessive cement use are significant CO_2 emissions, resource depletion, and dust generation. Furthermore, adding lime to clayey soil significantly increases its strength; nevertheless, the calcination of limestone to form lime releases carbon dioxide into the environment. Using fly ash as a soil additive not only increases the strength of the soil but also reduces or eliminates waste storage costs and adverse environmental effects. As the most significant scientific and technological domains of the twenty-first century, nanoscience and technology have the potential to transform the engineering sector and help to satisfy the needs of sustainable development. Among the many well-known nano additives, Nano-SiO_2 has been researched for over a decade and is considered to be the most

eco-friendly additives in geotechnical engineering. Furthermore, silicon dioxide, the essential component of Nano-SiO_2, is essentially harmless. Therefore, using it to improve soil is safe and beneficial for the environment.

The treatment and disposal of the ash produced by coal-based thermal power plants is a major challenge faced globally. This issue is complicated by the high ash concentration (30–50%) of Indian coal. Every year, the nation's coal-fired power plants create about 200 million tonnes of coal fly ash (CFA). The need for a big storage area and the safe disposal of the ash without negatively impacting the environment are the main issues. Therefore, rather than disposing of the ash, efforts are being undertaken to use it. The coal fly ash can be used in large quantities for geotechnical engineering applications such as sub-base construction, backfill, embankment construction, and as a stabilizing material for improving the strength of weak soils. Before this material can be used in bulk in fields as geomaterials, it is important to check the behaviour of the material under realistic loading conditions (static and cyclic/dynamic). Contributing to this objective, a comprehensive experimental program has been planned in the present study.

In the present study, an attempt has been made to examine the insight behaviour of the clayey soil, fly ash and Nano-SiO_2 (NS) collected from Begusarai, Bihar, India; Rihand NTPC Limited, Uttar Pradesh, India; and Fibrezone, Gujarat, India respectively. Also, the utilization of fly ash and Nano-SiO_2 (NS) for the strength improvement of clayey soil has been explored. Furthermore, along with the comprehensive physical, morphological, mineralogical, chemical, and geotechnical assessment, the strength characteristics of the clayey soil treated with Nano-SiO_2 and fly ash have been examined under large and small-strain conditions. The percentages of Nano-SiO_2 varied between 0.5-7% (0.5, 1, 3, 5 and7), and fly ash varied between 10-30% (10, 20, and 30) by weight of the soil. The optimal dosages of Nano-SiO_2 and fly ash were established by employing the outcome of the static test results. The cyclic triaxial (CTX) tests and bender element (BE) tests were carried out to determine the shear modulus (G) and damping ratio (D) of the composite material and to develop normalized modulus reduction (G/G_{max}) and damping ratio curves for the same. The strain-controlled cyclic triaxial tests were conducted for a shear strain range of 0.6-3.0% (0.6, 0.9, 1.2, 1.5, 2.1, 2.4, 2.7, and 3.0) at a loading frequency of 1 Hz and an adequate confining pressure of 100kPa at a curing age of 28 days. A set of 48 strain-controlled cyclic triaxial test were performed under consolidated undrained conditions for dynamic behaviour study of the clayey soil treated with Nano-SiO_2 and fly ash. Furthermore, normalized modulus reduction and damping ratio curves of the treated and untreated clayey soil have been plotted using the results of the cyclic triaxial and bender element tests.

The fly contains a larger amount of sand (76.02%), followed by silt (23.52%) and clay (0.44%). The fly ash classified as silty sand (SM). The soil has 1.3% sand, 66.67% silt, and 32% clay. The clay soil categorized as clay with high plasticity (CH). The shear strength was enhanced to approximately 232%, 295%, and 214% at 28 days of curing with the addition of 1% Nano-SiO_2 and different fly ash contents (10%, 20%, and 30%), respectively. The highest shear strength was obtained with 1% Nano-SiO_2 and 20% fly ash. The cementitious and pozzolanic reactions with the presence of siliceous or aluminous materials in the soil matrix or binding agent result in the development of calcium silicate hydrate (C-S-H) and calcium aluminate silicate hydrate (C-A-S-H) gel, which results in the strength growth rate of the specimens induced by the addition of fly ash. The maximum values of shear wave velocity (V_s) and thereby small-strain shear modulus (G_{max}) of soil matrix was achieved with 1% of Nano-SiO_2 and 20% of fly ash. A significant improvement in static strength and dynamic properties was noticed for the clayey soil treated with 1% Nano-SiO_2 and 20% fly ash compared to the untreated soil with the curing ages. The strength enhancement with the binders to the clay soil was due to the pozzolanic activity with the curing ages. The developed G/G_{max} and damping ratio curves fit the database well. The results can be useful for predicting the seismic behavior of the Nano-SiO_2 and fly ash-treated clayey soil under various strain conditions. In addition, the utilization of Nano-SiO_2 and fly ash-treated clayey soils in various civil engineering applications contributes towards sustainable development and a reduced carbon footprint.

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NOMENCLATURE

ε - axial strain

ρ - Bulk mass density

η - Porosity

υ - Poisson's ratio

λ - Wavelength

μ - Micron

γ_d - Dry unit weight

f - Frequency

CO_2 - Carbon dioxide

C_u - Coefficient of uniformity

C_c - Coefficient of curvature

MDD - Maximum dry density

OMC - Optimum moisture content

UCS - Unconfined compressive strength

UU - Unconsolidated undrained

CU – Consolidated undrained

LL - Liquid limit

PL - Plastic limit

PI - Plasticity index

SL - Shrinkage limit

CH - Clay with high plasticity

c - Cohesion

ϕ - Angle of internal friction

CSH - Calcium silicate hydrate

CASH - Calcium aluminate silicate hydrate

FA - Fly ash

NS - Nano silica

EDX - Energy Dispersive X-Ray

SEM - Scanning Electron Microscope

XRD - X-Ray Diffraction

XRF - X-Ray Fluorescence

FTIR - Fourier Transform Infrared Spectroscopy

CaO - Calcium oxide

$CaCO_3$ - Calcium carbonate

Al_2O_3 - Aluminium oxide

SiO_2 - Silicon oxide

CBR - California bearing ratio

IS - Indian standard

IRC - Indian road congress

ASTM - American Society for Testing and Materials

G - Dynamic shear modulus

D - Damping ratio

E - Young's modulus

B - Skempton's pore pressure parameter

r_u - Excess Pore pressure ratio

G_{max} - Maximum shear modulus

V_s - Shear wave velocity

L_{tt} - Travel distance

t - Time

G/G_{max} - Normalized shear modulus

γ - Shear strain

CP - Confining pressure

σ'_c - Effective confining pressure

σ_d - Deviator stress

Hz - Hertz

kHz - Kilohertz

kPa – Kilopascal

kN- Kilonewton

MPa - Megapascal

CTX - Cyclic triaxial test

K_T - Coefficient of permeability

L - length

A - area

kg - Kilogram

mm - Millimetre

G_s - Specific gravity