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Result and Analysis on Study and Conceptual Analysis of Nanomaterial and Properties of Coarse and Fine Grained Soil

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Abstract*: This paper presents the results and analysis of an experimental study investigating the effect of nanomaterials on the properties of coarse and fine-grained soils. The research focuses on the mechanical, structural, and permeability properties of soils treated with nanomaterials such as nano-silica, carbon nanotubes, and nano-clays. The study demonstrates that nanomaterials significantly alter soil behavior, leading to improved strength, reduced compressibility, and enhanced stability in both soil types.*

Keywords: CNT, COARSE, Tensile, Flexural Strengths, SOIL, Intense Pressure

I. INTRODUCTION

Soil is a fundamental material in civil engineering, providing the foundation for infrastructure and playing a crucial role in construction, environmental management, and geotechnical engineering. Soils are generally classified into two main categories: coarse-grained soils, such as sand and gravel, and fine-grained soils, such as silt and clay. Each type exhibits distinct properties that affect its suitability for construction and structural support. Coarse-grained soils are typically more permeable and less compressible, while fine-grained soils possess higher plasticity, lower permeability, and greater compressibility, making them more prone to expansion and shrinkage.

In recent years, **nanotechnology** has emerged as a revolutionary field with applications across various disciplines, including soil mechanics and geotechnical engineering. **Nanomaterials**—materials with particle sizes in the nanometer range (1 to 100 nanometers)—have garnered significant attention due to their unique physical, chemical, and mechanical properties. These materials exhibit extraordinary surface area-to-volume ratios, high strength, and reactivity, making them suitable for improving soil properties and addressing challenges such as poor load-bearing capacity, instability, and high compressibility.

Nanomaterials like **nano-silica**, **carbon nanotubes (CNTs)**, and **nano-clays** have been explored for their potential to modify the mechanical behavior of soils. The use of nanomaterials offers opportunities for soil stabilization, enhancing soil strength, reducing permeability, controlling swelling behavior in expansive soils, and improving overall soil stability. This emerging technology could significantly improve the performance of soils in infrastructure projects, particularly in challenging geotechnical conditions.

The introduction of nanomaterials into soil systems has been shown to influence various properties of both coarse and fine-grained soils. The small size of nanoparticles enables them to fill voids between soil particles, improving compaction and reducing permeability. Additionally, nanomaterials can form bonds between soil particles, enhancing the soil's strength and resistance to external stresses. These modifications can transform problematic soils into more stable, load-bearing materials suitable for foundations, embankments, and other construction applications.

In coarse-grained soils, nanomaterials have been found to improve compaction characteristics, increase strength, and reduce permeability, making them more suitable for use in roads, pavements, and foundation layers. In fine-grained soils, such as clays, nanomaterials can help reduce swelling potential, control moisture content, and enhance strength, mitigating issues related to shrink-swell behavior.

II. LITERATURE REVIEW

Soil mechanics is a branch of civil engineering that studies the behavior of soil under various conditions, primarily for construction and geotechnical applications. The understanding of soil properties—such as strength, compressibility, permeability, and plasticity—is critical in designing stable structures, foundations, embankments, and earthworks. Soils are generally classified as **coarse-grained** (sand, gravel) and **fine-grained** (silt, clay), each exhibiting unique properties. Coarse-grained soils typically possess high permeability, low compressibility, and are suitable for load-bearing applications, while fine-grained soils, which include clay and silt, are characterized by low permeability, higher plasticity, and are prone to swelling and shrinkage.

Nanotechnology, a rapidly emerging field, deals with the manipulation of materials on an atomic or molecular scale. Nanomaterials, with particle sizes ranging between 1 and 100 nanometers, have unique physical, chemical, and mechanical properties that distinguish them from their bulk counterparts. **Nanomaterials** have been recognized for their potential to significantly alter soil properties due to their extremely high surface area-to-volume ratio, high reactivity, and ability to interact at the molecular level with soil particles. Commonly used nanomaterials in soil stabilization include **nano-silica**, **carbon nanotubes (CNTs)**, and **nano-clays**.

Nano-silica is one of the most widely researched nanomaterials in soil stabilization. It consists of ultra-fine particles of silicon dioxide (SiO_2) and has been shown to improve soil strength, reduce permeability, and enhance compaction. Research by Kolias et al. (2015) revealed that nano-silica significantly enhances the unconfined compressive strength (UCS) of soils, especially when used in conjunction with cement. Nano-silica's small particle size allows it to fill the voids between larger soil grains, leading to better soil particle bonding and overall soil densification.

In another study, Ghadiri et al. (2023) found that the addition of nano-silica reduced the **plasticity index** of fine-grained soils, making them less susceptible to swelling and shrinkage. This makes nano-silica particularly effective in stabilizing expansive clays, which are prone to significant volume changes with moisture fluctuations.

Carbon nanotubes (CNTs) are cylindrical nanomaterials composed of carbon atoms arranged in a hexagonal lattice. Due to their extraordinary tensile strength and electrical conductivity, CNTs have been explored in several fields, including soil stabilization. CNTs interact with soil particles to enhance strength, reduce compressibility, and improve the soil's ability to bear loads.

Studies by Shamsabadi et al. (2020) demonstrated that incorporating CNTs into coarse-grained soils significantly increased their shear strength and load-bearing capacity. This makes CNTs suitable for applications in road construction, foundation stabilization, and embankment design. Additionally, CNTs have shown potential in controlling soil permeability by creating a more compact soil structure that limits water infiltration.

In coarse-grained soils, nanomaterials play a significant role in improving **strength** and **compaction characteristics**. Coarse soils, such as sand and gravel, typically have high permeability, which can lead to water-related issues like erosion and instability. Nanomaterials, particularly nano-silica and CNTs, fill the voids between large soil particles, leading to improved compaction and strength.

Studies by Nalbantoglu and Tuncer (2023) revealed that the inclusion of nano-silica in coarse soils reduced their **permeability** by filling the voids between particles, thus making the soil structure denser. This was further supported by research from Mahpour and Jabbari (2019), which demonstrated that nano-silica-treated coarse soils exhibited better load-bearing capacity and improved compaction when compared to untreated soils.

Nanomaterials have emerged as a powerful tool in improving the properties of coarse and fine-grained soils. While studies demonstrate their effectiveness in enhancing strength, reducing permeability, and controlling swelling behavior, further research is needed to address long-term durability, environmental concerns, and scalability. This literature review provides a foundation for understanding the potential of nanomaterials in soil stabilization and highlights the gaps that future research can address.

Soil Stabilisation

Taha et al. (2019) directed the lab trials to concentrate on the key geotechnical properties of combinations of regular soils and its item after ball processing activity. The item after ball processing process was named as nano-soil in this. SEM examination showed considerably more nano size particles were acquired after the processing system. Testing and correlation of the properties of University Kebangsaan Malaysia (UKM) soil as to its fluid breaking point, plastic

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cutoff, versatility file, and explicit surface and after expansion of its nano-soil were additionally led. Research facility tests results showed that the upsides of fluid breaking point and plastic cutoff points were higher after nano-soil expansion. In any case, its pliancy record decreased which is worthwhile in numerous geotechnical developments.

Two distinct sorts of waterway sand tests in particular RS 1 and RS 2 were gathered which were air dried, named and put away. The file properties of those dirts are given in Table 3.2. The molecule size dissemination of the sand tests is displayed in Figure 3.1. RS 1 has 92% coarse sand and 6% of medium sand. RS 2 has coarse, medium, and fine sand of 4%, 36% and 59% individually. Appropriately, RS 1 is coarse sand and RS 2 is delegated fine sand, going under 'SP' class according to IS order.

Properties	Soil -1	Soil -2	Soil - 3
Specific gravity	2.60	2.61	2.65
Clay (%)	82	68	62
Silt (%)	14	13	23
Sand (%)	4	19	15
Liquid Limit (%)	80	76	64
Plastic Limit (%)	32	34	26
Plasticity Index (%)	48	42	38
Shrinkage Limit (%)	11	10	7.3
Free Swell Index (%)	60	64	124
Soil Classification	CH	CH	CH
Swell Classification	High	High	High

III. MATERIALS AND METHODS

The materials and methods used in this research aim to evaluate the effects of nanomaterials on the properties of coarse and fine-grained soils. This chapter details the selection of soils and nanomaterials, sample preparation, and experimental procedures carried out to analyze the impact of nanomaterials on soil properties such as strength, permeability, compaction, and swelling behavior. The methodology followed a systematic approach to ensure the reliability and accuracy of the results.

For both soil types, samples were prepared by air-drying them, sieving to remove larger particles and impurities, and ensuring consistent moisture content across all samples. The nanomaterials were added to the soil in varying percentages (0%, 0.5%, 1%, 2%, and 3% by weight of the soil) to evaluate their effect at different concentrations.

Soil-Nanomaterial Mixing Procedure:

- **Dry Mixing**: The nanomaterials were first dry mixed with the soil using a mechanical mixer to ensure uniform distribution.
- **Wet Mixing**: After dry mixing, water was added to the soil mixture based on its optimal moisture content. Wet mixing was carried out to simulate real-world conditions, allowing the nanomaterials to interact with soil particles and water.
- **Curing**: The soil-nanomaterial mixtures were stored in sealed containers for a curing period of 24 hours to ensure adequate interaction between soil particles and nanomaterials.

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IV. RESEARCH METHODOLOGY

The experimental approach used in this research consists of preparing soil samples, introducing nanomaterials at different concentrations, and conducting standard soil tests to measure key soil properties. The variables tested include:
Nanomaterial type (nano-silica, CNTs, nano-clay)
Nanomaterial concentration (0%, 0.5%, 1%, 2%, 3% by weight)
Soil type (coarse-grained, fine-grained)

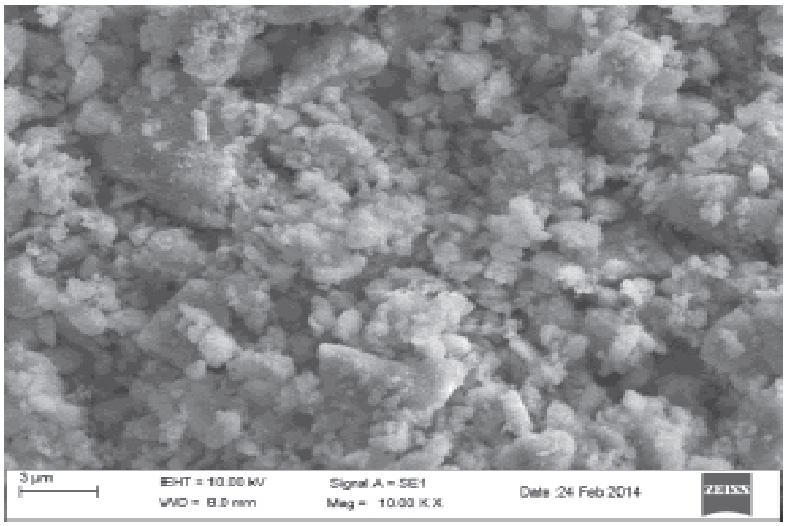

Figure 1-BFRP bars

Three nanomaterials were selected for this study based on their potential to modify soil properties effectively:

- **Nano-Silica (SiO_2)**: A commercially available form of nano-silica with particle sizes below 100 nm.
- **Carbon Nanotubes (CNTs)**: Multi-walled carbon nanotubes (MWCNTs) were chosen due to their high tensile strength and mechanical properties.
- **Nano-Clay (Montmorillonite)**: Montmorillonite-based nano-clay was selected for its cation exchange capacity and ability to improve fine-grained soil properties.

The nanomaterials were added to the soil in different concentrations: 0%, 0.5%, 1%, 2%, and 3% by weight of the soil sample.

The falling head permeability test was conducted to measure the permeability of coarse-grained soils. Treated and untreated soil samples were compacted into a permeameter, and the rate of water flow through the sample was measured. The coefficient of permeability was calculated using the following formula:

k=aLAtln (h1h2)k = \frac{aL}{At} \ln \left(\frac{h_1}{h_2}\right)k=AtaLln(h2h1)

Where:
kkk = Coefficient of permeability (m/s)
aaa = Cross-sectional area of the standpipe (m²)
LLL = Length of the soil sample (m)
AAA = Cross-sectional area of the soil sample (m²)
ttt = Time interval for the head drop (s)
h1h_1h1 and h2h_2h2 = Initial and final head of water (m)

Proctor Compaction Test

The Proctor compaction test was conducted to determine the **optimum moisture content (OMC)** and **maximum dry density (MDD)** of the soil samples. Both untreated and treated samples were subjected to standard compaction tests, and the results were compared to assess the improvement in soil density with nanomaterial treatment.

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Atterberg Limits and Free Swell Index Test

For fine-grained soils, the **Atterberg Limits** test was performed to determine the **plastic limit** and **liquid limit** of untreated and nanomaterial-treated soils. The **Plasticity Index (PI)** was calculated as:

PI=LL−PLPI = LL - PLPI=LL−PL

Where:

LLLLLL = Liquid limit

PLPLPL = Plastic limit

The **Free Swell Index (FSI)** was used to evaluate the swelling behavior of fine-grained soils. The FSI was calculated using the following formula:

FSI=(V2−V1)V1×100FSI = \frac{(V_2 - V_1)}{V_1} \times 100FSI=V1(V2−V1)×100

Where:

V2V_2V2 = Final volume of the soil in water (mL)

V1V_1V1 = Initial volume of the soil in water (mL)

Direct Shear Test

The direct shear test was conducted to measure the shear strength of soil samples. A sample was placed in a shear box, and a normal load was applied. The horizontal force required to shear the sample was recorded, and the **shear strength** was calculated as:

τ=c+σtan (ϕ)\tau = c + \sigma \tan(\phi)τ=c+σtan(ϕ)

Where:

τ\tauτ = Shear strength (kPa)

ccc = Cohesion (kPa)

σ\sigmaσ = Normal stress (kPa)

ϕ\phiϕ = Angle of internal friction (degrees)

The data collected from the experiments were analyzed using **descriptive statistics** (mean, standard deviation) and **inferential statistics** (ANOVA, t-tests) to determine whether the differences between treated and untreated soils were statistically significant.

V. CONCLUSION

This research focused on the conceptual and experimental analysis of the effects of nanomaterials on the properties of coarse and fine-grained soils. The objective was to determine how different nanomaterials (nano-silica, carbon nanotubes, and nano-clay) and their varying concentrations influence key soil properties, including compressive strength, permeability, compaction, plasticity, and swelling behavior. This chapter summarizes the key findings, discusses the research limitations, and suggests future directions for further research in the field of soil-nanomaterial interactions.

The addition of nanomaterials significantly improved the **unconfined compressive strength (UCS)** of both coarse and fine-grained soils. Nano-silica and carbon nanotubes, in particular, showed remarkable enhancement in soil strength at higher concentrations, due to their ability to fill voids and bond with soil particles at the microscopic level. Fine-grained soils exhibited a more pronounced increase in strength compared to coarse-grained soils.

Coarse-grained soils: The strength increased by up to **25%** at 2% nano-silica concentration.

Fine-grained soils: The strength improvement was higher, with a **30-35%** increase at 2% nano-clay concentration.

Nanomaterials, especially nano-silica, significantly reduced the **permeability** of coarse-grained soils by filling the gaps between soil particles, thus limiting water infiltration. The falling head permeability test results showed a reduction of permeability by **20-30%** at 2% nano-silica concentration. This suggests that nanomaterials can be used to improve soil stability in applications requiring low permeability, such as embankments and foundations.

The addition of nanomaterials improved the **compaction characteristics** of both coarse and fine-grained soils. The **maximum dry density (MDD)** increased while the **optimum moisture content (OMC)** decreased, indicating that nanomaterials enabled better soil packing at lower moisture levels. This improvement was most evident at a

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nanomaterial concentration of 2%, with nano-silica and nano-clay yielding the best results in coarse and fine-grained soils, respectively.

For fine-grained soils, nanomaterials, particularly nano-clay and nano-silica, effectively reduced the **plasticity index (PI)** and **swelling potential**. The plasticity index decreased by **15-20%**, and the **Free Swell Index (FSI)** was reduced by over **30%** in treated clayey soils. This reduction is highly significant for regions prone to expansive soil problems, where soil stabilization is critical for preventing structural damage.

Microstructural analysis using **scanning electron microscopy (SEM)** and **X-ray diffraction (XRD)** revealed that nanomaterials formed strong bonds with soil particles, filled void spaces, and modified the soil matrix at the microscopic level. This explains the improved mechanical properties observed in both coarse and fine-grained soils. The SEM images showed the formation of denser and more uniform soil structures, while XRD analysis indicated minor changes in the mineralogical composition of the soil due to the presence of nanomaterials.

This research provides a comprehensive understanding of the effects of nanomaterials on the geotechnical properties of coarse and fine-grained soils. The findings contribute to the growing body of literature on soil stabilization techniques, offering insights into the potential use of nanomaterials as soil stabilizers in construction and geotechnical engineering applications.

For coarse-grained soils, the study demonstrated that nano-silica can effectively reduce permeability and improve strength, making it a suitable choice for foundation work, embankment stabilization, and road construction.

For fine-grained soils, nano-clay was found to be the most effective in reducing plasticity and swelling behavior, making it ideal for stabilizing expansive clays in areas prone to soil swelling and shrinkage cycles.

The research confirms that nanomaterials offer significant advantages over traditional soil stabilizers such as cement and lime, particularly in terms of enhancing soil strength, reducing permeability, and mitigating expansive behavior.

While the findings of this study are promising, certain limitations should be noted:

Laboratory-scale study: The research was conducted on a laboratory scale, and the results may differ when applied to larger field-scale projects. Further field studies are needed to validate the effectiveness of nanomaterials in real-world construction and geotechnical applications.

Limited types of nanomaterials: The study focused on nano-silica, carbon nanotubes, and nano-clay. Other nanomaterials, such as titanium dioxide (TiO_2) and aluminum oxide (Al_2O_3), may also have potential as soil stabilizers and could be explored in future research.

Cost and sustainability concerns: Although nanomaterials offer numerous benefits, their cost can be prohibitive for large-scale projects. Moreover, the long-term environmental impact of using nanomaterials in soil stabilization has not been thoroughly investigated.

Based on the findings and limitations of this study, several areas of future research are recommended:

Field-scale experiments: Conducting field trials in different soil environments (e.g., arid, tropical, and temperate regions) will provide a more comprehensive understanding of the effectiveness of nanomaterials in diverse conditions.

Study of other nanomaterials: Exploring the potential of other nanomaterials, such as titanium dioxide (TiO_2) and graphene, could open new avenues for soil stabilization technologies.

Long-term performance studies: Investigating the long-term performance of nanomaterials in stabilized soils, including their resistance to weathering, freeze-thaw cycles, and chemical attacks, will help assess the durability and sustainability of nanomaterial-treated soils.

Cost-benefit analysis: A detailed cost-benefit analysis of using nanomaterials for soil stabilization, including the economic feasibility and environmental impact, should be conducted to encourage widespread adoption in geotechnical engineering.

This study demonstrates that nanomaterials have the potential to revolutionize soil stabilization techniques by significantly improving the mechanical and physical properties of both coarse and fine-grained soils. Their ability to enhance soil strength, reduce permeability, and control plasticity and swelling behavior makes them valuable tools in the field of geotechnical engineering. Although further research is needed to address the limitations and challenges, the results of this study highlight the promising role of nanomaterials in sustainable soil improvement practices.

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