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Performance of marble powder – Nano silica stabilized clay

Pooja. M. Vijay *, Bhagya. S. A, Muhammed Al Ameen, Indrajith. S. M and Aanand. A

Department of Civil Engineering Vidya Academy of Science and Technology, Technical Campus Kilimanoor, Thiruvanthapuram, Kerala, India.

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Abstract

Clayey soils often exhibit unfavorable engineering characteristics such as low bearing capacity, high plasticity, and significant swelling, which limit their direct application in pavement and foundation construction. Soil stabilization is widely adopted to enhance the performance of such problematic soils. This study evaluates the effectiveness of marble powder, an industrial waste material, and nano- silica, a highly reactive nanomaterial, as stabilizing agents for clayey soil.

A series of laboratory investigations were conducted on natural and stabilized soil samples with varying proportions of marble powder and nano-silica. The experimental program included Atterberg limits, Standard Proctor compaction, Unconfined Compressive Strength (UCS), California Bearing Ratio (CBR), and Free Swell Index (FSI) tests, performed in accordance with relevant Indian Standard codes.

The results demonstrate that the incorporation of marble powder leads to a reduction in plasticity and an improvement in compaction characteristics, while nano-silica significantly enhances strength through micro-level bonding and pozzolanic reactions.

An optimum stabilizer combination of 10% marble powder and 0.5% nano-silica was identified, yielding maximum strength improvement and a substantial reduction in swelling behavior. The findings indicate that the combined use of marble powder and nano-silica provides a sustainable, cost-effective, and environmentally friendly approach for improving the engineering performance of clayey soils for subgrade and foundation application.

Keywords: Soil Stabilization; Marble Powder; Nano-Silica; Clayey Soil; UCS; CBR; Swelling

1. Introduction

Rapid urbanization and infrastructure development have increased the demand for construction on marginal and weak soils. Among them, clayey soils are widely encountered and are often characterized by low bearing capacity, high plasticity, excessive compressibility, and significant swelling–shrinkage behavior. These unfavorable engineering properties pose serious challenges in the design and performance of pavements, embankments, and shallow foundations. Without proper treatment, clayey subgrades are prone to deformation, cracking, and premature structural failure.

Soil stabilization is a proven and widely adopted technique to improve the engineering characteristics of problematic soils. Conventional stabilizers such as cement and lime have been extensively used to enhance soil strength and durability; however, their application is associated with high material costs, increased energy consumption, and

* Corresponding author: Pooja. M. Vijay

significant carbon dioxide emissions. In recent years, the focus of geotechnical research has shifted toward the utilization of industrial waste materials and advanced additives as sustainable alternatives for soil stabilization.

Marble powder is a by-product generated in large quantities during marble cutting and polishing operations. Improper disposal of marble waste leads to environmental degradation and land pollution. Owing to its fine particle size and high calcium carbonate content, marble powder exhibits potential for use as a soil stabilizing agent by reducing plasticity, filling voids, and improving compaction behavior. The effective utilization of marble powder not only enhances soil properties but also contributes to waste management and sustainable construction practices.

Nanomaterials have recently gained considerable attention in geotechnical engineering due to their unique physicochemical properties. Among them, nano-silica is highly reactive and possesses an extremely large specific surface area, which enables it to improve inter-particle bonding at the microstructural level. Nano-silica participates in pozzolanic reactions in the presence of calcium, leading to the formation of calcium-silicate-hydrate (C–S–H) gel, which significantly enhances soil strength and stiffness while reducing permeability and swelling.

Although several studies have investigated the individual effects of marble powder and nano-silica on soil stabilization, limited research is available on their combined application for improving the engineering performance of clayey soils. The synergistic interaction between marble powder as a calcium source and nano-silica as a highly reactive pozzolan may result in superior strength development and swelling control.

Therefore, the present study aims to evaluate the effectiveness of marble powder and nano-silica as combined stabilizing agents for clayey soil through a comprehensive laboratory investigation. The study focuses on assessing changes in plasticity, compaction characteristics, strength parameters, and swelling behavior, with the objective of identifying an optimum stabilizer combination suitable for pavement subgrade and foundation applications.

2. Literature Review

Numerous studies have been carried out to improve the engineering properties of weak clayey soils using conventional and alternative stabilization techniques. This section reviews previous research on the use of industrial waste materials and nanomaterials, particularly marble powder and nano-silica, for enhancing the strength and reducing the swelling behavior of clayey soils.The published studies on alternative and sustainable construction materials were examined to assess the current state of knowledge on partial replacement of cement and fine aggregate.

2.1. Investigation on Use of Silica-Based Additive for Sustainable Subgrade Construction

Authors: Supriyo Morik, G. D. Ransinchung, R. N. Garg, Aditya Singh, Prathmesh Khot

This study investigated the application of a silica-based additive combined with cement for stabilizing weak subgrade soils. Laboratory tests including compaction characteristics, California Bearing Ratio (CBR), and Unconfined Compressive Strength (UCS) were conducted at varying additive contents. Microstructural analyses using XRD and SEM were performed to understand the stabilization mechanism. The results indicated significant improvements in UCS and CBR due to the formation of calcium–silicate–hydrate (C–S–H) gel. The study highlighted that silica-based additives enhance strength and durability while reducing pavement thickness and overall construction cost, making the method sustainable for subgrade improvement.

2.2. The Efficiency of Waste Marble Powder in the Stabilization of Fine-Grained Soils in Terms of Volume Changes

Authors: Osman Sivrikaya, Firdevs Uysal, Ayşegül Yorulmaz, Kemal Aydın

This research examined the effectiveness of waste marble powder in reducing volume change behavior of fine-grained soils. Different proportions of calcitic and dolomitic marble powders were added to clayey soils, and laboratory tests such as Atterberg limits, linear shrinkage, swelling index, and consolidation tests were conducted. The results showed a significant reduction in plasticity index, swelling potential, and compressibility with increasing marble powder content. The study concluded that waste marble powder is an efficient stabilizer for controlling swelling and shrinkage in fine- grained soils.

2.3. Marble Powder as a Soil Stabilizer:

An Experimental Investigation of the Geotechnical Properties and Unconfined Compressive Strength Analysis

Authors: Ibrahim Haruna Umar, Hang Lin

This experimental study evaluated waste marble powder as an alternative stabilizing material for fine-grained soils. Tests such as Atterberg limits, compaction characteristics, CBR, indirect tensile strength, and UCS were conducted at varying marble powder contents and curing periods. The results demonstrated an increase in UCS and CBR values with optimum marble powder content, while plasticity and swelling reduced. The study emphasized marble powder's pozzolanic action and void-filling ability, confirming its suitability as a cost-effective soil stabilizer.

2.4. A Review on the Choice of Nano-Silica as Soil Stabilizer

Authors: G. Kannan, E. R. Sujatha

This review paper presented a comprehensive assessment of nano- silica as a soil stabilizing agent. The authors analyzed previous research focusing on nano-silica's physical characteristics, reaction mechanisms, curing behavior, and performance in different soil types. The review highlighted that nano-silica significantly improves strength, reduces hydraulic conductivity, and enhances durability due to its high surface area and pozzolanic reactivity. The paper also discussed challenges related to field implementation and emphasized the need for further practical investigations.

2.5. Stabilization of Marble Wastes Using Cement and Nano- Materials for Subgrade Applications

Authors: A. S. Pateria, D. J. Robert, K. Dharavath, S. K. Soni

This study investigated the stabilization of marble waste using cement and nanomaterials for subgrade applications. Marble waste was initially stabilized with cement and further enhanced using nano- additives. Strength improvement was evaluated through UCS and CBR tests, along with microstructural analyses. The results showed a remarkable increase in strength and durability due to improved bonding and densification. The study recommended stabilized marble waste as a sustainable alternative subgrade material for pavement construction.

2.6. Performance Enhancement of Cementitious Soil Stabilizers Using Incorporated Nano-Silica

Authors: Ebrahim Najafi Koni, Amir Hossein Rofeian, Mohsen Tavakolzadeh, Seyed Hamidreza Ghaffar

This research focused on the role of nano-silica in improving cement- based soil stabilizers. Mechanical tests and microstructural analyses (SEM, XRD, FTIR) were conducted to evaluate strength and bonding behavior. The results revealed that nano-silica significantly increased UCS and elastic modulus by promoting denser C–S–H formation and better particle interlocking. The study confirmed nano-silica's effectiveness in enhancing ductility and strength of stabilized soils.

2.7. Use of Nanomaterials in Underlying and Subgrade Soil Stabilisation: A Review

Authors: Martina Gausmar Sorum, Neero Gausmar Sorum

This review critically evaluated the application of nanomaterials in soil stabilization based on extensive literature. The study identified nano-silica as the most widely used nanomaterial for improving soil strength, reducing plasticity, and enhancing durability. The review highlighted mechanisms such as void filling, pozzolanic reactions, and microstructural densification. The authors also discussed limitations related to cost, scalability, and environmental impact, recommending further field-level research.

2.8. The Impact of Nano-Silica and Nano-Silica-Based Compounds on Strength, Mineralogy and Morphology of Soil: A Review

Authors: Vaibhav Chaudhary, Jitendra Singh Yadav, Rakesh Kumar Dutta

This review summarized the influence of nano-silica on soil strength, mineralogical changes, and morphological behavior. The study reported that nano-silica significantly enhances strength and stiffness by filling micro-voids and improving interparticle bonding. Pozzolanic reactions and improved particle arrangement were identified as the primary stabilization mechanisms. The review concluded that nano-silica-based compounds are highly effective for stabilizing problematic soils.

2.9. Pursuance of Waste Marble Powder to Improve Soil Stabilization

Authors: Riddhi Choksi, C. B. Mishra, Nandan Patel

This study investigated the effect of waste marble powder on the engineering properties of clayey soils. Laboratory tests such as liquid limit, plastic limit, compaction, CBR, and UCS were conducted at various marble powder contents. The results showed a reduction in plasticity and swelling, along with improved strength characteristics. The study concluded that waste marble powder is an economical and environmentally friendly soil stabilizer for pavement subgrades.

2.10. Laboratory Testing and Analysis of Clay Soil Stabilization Using Waste Marble Powder

Authors: Ibrahim Haruna Umar, Hang Lin, Anas Sadiq Ibrahim

This research evaluated the stabilization of clayey soil using waste marble powder through laboratory testing and analytical modeling. Tests included Atterberg limits, compaction, UCS, and ultrasonic pulse velocity. The results indicated a significant improvement in strength and stiffness at optimum marble powder content and curing time. Artificial neural network (ANN) modeling accurately predicted soil behavior, confirming the effectiveness of waste marble powder in soil stabilization.

2.11. Soil Stabilization with Nanomaterials and Extraction of Nanosilica: A Review

Authors: Karumanchi Meeravali, Nerella Ruben, Mikkili Indira

This review paper discusses the application of nanomaterials, particularly nanosilica, in the stabilization of weak and soft clayey soils. It highlights the bonding capability of nanomaterials with soil particles and explains how nanosilica improves soil strength and durability. The study also reviews methods for extracting nanosilica from agricultural waste and characterizing it using techniques such as XRD, EDS, and FTIR. The paper emphasizes the potential of nanotechnology in geotechnical engineering applications.

2.12. Experimental and Numerical Study on Nano-Silica-Stabilized Clayey Subgrades with Geogrid Support

Authors: Lassana P. Dukuly, Sufyan Ghani, Sunayana Kushwaha

This research presents both laboratory experiments and numerical simulations on clayey subgrades stabilized with nano-silica and reinforced with geogrids. Nano-silica content ranging from 0–4% was evaluated, with optimal performance observed at 2.5%. The study shows improvements in plasticity, strength, density, bearing capacity, and settlement reduction. Numerical modeling confirmed that combining chemical stabilization (nano-silica) with mechanical reinforcement (geogrid) significantly enhances pavement subgrade performance.

2.13. Activation of Marble Industry Waste for Sustainable Stabilization of Clays

Authors: Francesco Moscato, Marco Rosone, Clara Calauro, Alessio Ferrari

This paper investigates the reuse of marble industry waste sludge as a sustainable stabilizing agent for clay soils. The waste material was activated through calcination and used as a binder in clay–binder mixtures. Laboratory tests such as compaction, swelling, oedometer compression, and unconfined compression strength were conducted. Results demonstrate that activated marble waste improves the mechanical behavior of clay soils, offering an environmentally friendly alternative to traditional cement and lime stabilizers.

2.14. Clayey Soil Stabilization Using Waste-Derived Pine Needles and Marble Dust: An Experimental Evaluation

Authors: Muhammad Zeeshan Ahmad, Muhammad Tayyab Jan, Mohsin Ahmad, Irfan Jamil, Sogmiai Shahab

This experimental study examines the stabilization of clayey soil using pine needles and marble dust, both of which are waste materials. Laboratory tests such as Modified Proctor, UCS, CBR, permeability, and swelling tests were performed. The combined use of pine needles and marble dust improved soil strength, reduced swelling and permeability, and enhanced load-bearing capacity. The study highlights the economic and environmental benefits of using waste materials for sustainable soil stabilization.

2.15. Nanomaterials in Geotechnical Engineering: A Comprehensive Review on Soil Improvement Techniques

Author: Meysam Bayat

This comprehensive review focuses on the use of nanomaterials in soil improvement and geotechnical engineering. It summarizes recent research on nanoparticles used for soil stabilization and explains the mechanisms through which

nanomaterials enhance soil properties. The paper discusses synergies between nanomaterials and traditional stabilizers, emphasizing sustainability, performance improvement, and future research directions in nanotechnology-based ground improvement.

2.16. Stabilised Soil Properties Using Waste Marble Powder:

A Review Author: Dr. Nuha S. Mashaan

This review evaluates the influence of waste marble powder on the physical and mechanical properties of soil. It discusses the effects of marble powder on compaction, plasticity, permeability, UCS, and CBR values. The paper highlights the environmental advantages of recycling marble waste in construction and identifies challenges and research gaps for optimizing its use in soil stabilization practices.

2.17. Nanosilica as an Auxiliary Additive in Behaviour Enhancement of Weak Soil Subgrade

Authors: Pavithra Sakthi Vinayagam, Sivapriya Vijayasimhan, Thanikachalam Muniappan

This study evaluates nanosilica as a secondary additive used alongside lime for improving weak soil subgrades. Unconfined compression strength, durability, and CBR tests were conducted for various curing periods. Results show significant increases in strength, durability, and bearing capacity, along with reduced pavement thickness requirements. The study confirms nanosilica's effectiveness in enhancing both short-term and long-term performance of stabilized soils.

2.18. Effectiveness of Marble Powder to Improve Compaction of Low-Water-Content Soil

Authors: Oubaida AICHE, Mohamed KHAITINE, Amel MEDJOUNI, Ramdane BAHAR

This paper investigates the use of marble powder to improve soil compaction under low water content conditions, particularly in arid regions. Laboratory tests showed that adding marble powder increased maximum dry density and CBR values while reducing optimum moisture content. The study demonstrates that marble powder is a cost-effective and sustainable alternative for improving subgrade soils in water-scarce environments.

3. Conclusion

This study investigated the effectiveness of marble powder and nano- silica as stabilizing agents for improving the engineering properties of clayey soil. Laboratory test results indicate that the addition of marble powder significantly reduced soil plasticity and improved compaction characteristics by modifying the soil gradation and filling micro-voids within the soil structure. The incorporation of nano-silica further enhanced soil strength due to micro-level bonding and accelerated pozzolanic reactions, leading to the formation of cementitious calcium–silicate–hydrate (C–S–H) gel that strengthened inter-particle connections.

The combined application of both materials resulted in notable improvements in unconfined compressive strength and California Bearing Ratio, along with a substantial reduction in swelling behavior and compressibility. This synergistic effect highlights the role of marble powder as a calcium-rich material and nano-silica as a highly reactive pozzolanic additive, together contributing to improved soil stiffness and durability. An optimum stabilizer content of 10% marble powder and 0.5% nano-silica was identified as providing the best overall performance in terms of strength enhancement, volume stability, and compaction efficiency.

The findings demonstrate that the use of marble powder and nano- silica offers a sustainable, cost-effective, and environmentally friendly solution for the stabilization of clayey soils in pavement subgrade and foundation applications. The reuse of marble industry waste reduces the demand for conventional stabilizers such as cement and lime, thereby lowering construction costs and associated carbon emissions. Moreover, the improved resistance to moisture-induced deformation suggests enhanced long-term performance under cyclic wetting and drying conditions. Overall, the proposed stabilization approach presents a promising alternative for sustainable geotechnical engineering practice and can be effectively adopted in infrastructure projects requiring improved subgrade performance.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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