



Eco-Smart Geomaterials and Nano-Engineered Soils: Innovations in Geotechnical Engineering for Pollution Mitigation and Environmental Sustainability

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ABSTRACT

Nanotechnology and smart materials have emerged as crucial fields for building, analyzing, and studying soil-related infrastructure systems with enhanced performance and sustainability. This review covers the recent progress in nano-engineered soils and smart materials, including their types and mechanisms of interaction with soil matrices, and further explains their prospective applications in stabilization, reinforcement, sensing, and ground improvement technologies. Widely used nanomaterials, such as nano-silica, nano-clay, carbon nanotubes, graphene, and nano-calcium carbonate, have great potential to enhance geotechnical properties, including shear strength, compressibility, and permeability. A novel approach using smart materials, including piezoelectric materials, shape memory alloys (SMAs), electroactive polymers, and self-healing composites, bestows adaptive functions and integrated sensing capabilities upon soil systems, enabling real-time monitoring and adaptive behavior. This review also discusses the environmental consequences and sustainability considerations of implementing these advanced materials. In this regard, aspects of life cycle assessment (LCA), potential toxicity, and bioaccumulation risks are also highlighted, and the potential of eco-friendly and bio-inspired alternatives is highlighted as part of promoting green geotechnical practices and models of the circular economy. With advances on the horizon, the public implementation of these materials is impeded by challenges, including challenges with their dispersion, their long-term performance, their high costs, the lack of verifiable guidelines, and regulatory frameworks. Finally, the paper concludes with directions for future research, such as the necessity for field-scale validations, integration with Artificial Intelligence and Internet of Things technologies for smart soil systems, and formulation of eco-friendly, bio-compatible nanomaterials. This review emphasizes that nano-engineered soils and smart materials can reshape geotechnical engineering and offers forward-looking perspectives on how asset (infrastructure) owners and the construction industry may benefit from resilient, intelligent, and sustainable solutions.

INTRODUCTION

Geotechnical engineering, an essential subdiscipline of civil engineering, involves the design and construction of structures. It helps maintain natural trends and forces with man-made structures when building infrastructure (Acharya 2024, Pandey 2025). In particular, soils as natural materials are subjected to considerable variability in their composition, texture, structure, and moisture content from one location to another and even over short spatial distances. Such variations frequently

yield erratic performance under loading or externally driven environmental changes, which generate geotechnical problems such as excessive settlement, slope failures, liquefaction, expansive soil behavior, and poor drainage characteristics. Additionally, the unprecedented frequency of extreme weather events induced by climate change (e.g., heavy rain, droughts, and high groundwater levels) has rendered infrastructure systems vulnerable to failure, making geotechnical dependability an issue of paramount importance in contemporary resilient infrastructure development (Acharya 2024, Kandalai et al. 2023).

Manipulation of matter at the atomic, molecular, or supramolecular level within the size range of 1 to 100 nm is known as nanotechnology, and it has become a revolutionary force in many fields of science and engineering. Nanomaterials possess special and superior qualities in geotechnical engineering, including high surface area-to-volume ratios, improved chemical reactivity, greater bonding potential, and remarkable mechanical strength (Ulusoy 2023, Mola-Abasi et al. 2025, Harilal et al. 2024, Harsh et al. 2023). These substances can significantly improve geotechnical properties, such as shear strength, compressibility, permeability, swelling potential, and erosion resistance, when added to soils. For instance, in cement-treated soils, it has been discovered that nano-silica and calcium hydroxide react pozzolanically, increasing strength and decreasing the porosity. Because of their high aspect ratio and surface charge, nanoclays help retain water and promote cohesiveness, which might be useful in areas that are sensitive to moisture or in lining applications. Because of their remarkable tensile strength, stiffness, and thermal conductivity, carbon nanotubes (CNTs) and graphene derivatives are being investigated as reinforcements in soil composites to enhance load distribution and long-term durability (Siraj et al. 2022, Asim et al. 2022, Sabet 2024, Yadav et al. 2021).

The rise of nanotechnology coincides with the increasing use of smart materials, which are sophisticated substances capable of sensing environmental changes and responding in real time, either by modifying their properties or by activating specific functions (Karim et al. 2024, Ramakrishnan et al. 2022, Husen and Siddiqi 2023). Smart materials are increasingly used in geotechnical monitoring, adaptive construction, and self-healing infrastructure systems. Piezoelectric materials can convert mechanical strain into electrical signals, rendering them suitable for real-time stress and vibration sensing in foundations and slopes. Shape memory alloys (SMAs) can revert to a predetermined configuration when subjected to heat. Their potential applications are being explored in adaptive shoring systems and seismic isolation (Fang & Wang 2020, Tabrizikahou et

al. 2022, Huang 2024). Self-healing materials, which utilize microcapsules or bacteria to release healing agents upon the formation of cracks, enhance the durability of soil-cement or concrete-soil composites by facilitating automatic repair of micro-damage (Kurzeqar et al. 2024, Wagh, George, et al. 2025, Wagh, Waghmare, et al. 2025). Electroactive polymers and fiber optic sensors integrated into smart geotextiles provide continuous monitoring, facilitating early warning systems for landslides, sinkholes, and differential settlement (Kandalai et al. 2023, Pandey 2025, Acharya 2024).

The incorporation of nanomaterials and smart materials in geotechnical engineering presents significant opportunities for advancing intelligent and sustainable infrastructure systems (Firoozi et al. 2025, Imoni et al. 2023, Abedi 2024).

This study is significant because of its comprehensive and interdisciplinary approach. This paper integrates insights from geotechnical engineering, nanoscience, materials engineering, and environmental sustainability to present a vision that addresses critical global challenges. Specifically, the findings support the pursuit of several United Nations Sustainable Development Goals (SDGs), including the following:

SDG 9: Industry, innovation, and resilient infrastructure

SDG 11: Sustainable cities and communities

SDG 13: Climate action

RISE OF NANOTECHNOLOGY AND SMART MATERIALS IN CIVIL AND GEOTECHNICAL ENGINEERING

Nanomaterials improve the geotechnical properties of soil by functioning at the micro- to nanoscale within the soil matrix. Upon introduction to the soil, nano-additives such as nano-silica or nano-clay penetrate and occupy the spaces between soil particles, leading to a reduction in porosity and an increase in density. Cementitious reactions occur concurrently owing to pozzolanic activity, wherein nanoparticles react with calcium hydroxide to produce calcium silicate hydrate (C-S-H), thus enhancing the strength and cohesion of the soil. In advanced applications, carbon nanotubes (CNTs) are integrated into the soil matrix to create a network that can detect stress and strain. Nanomaterials enhance stabilization, reinforcement, and intelligent sensing, resulting in more resilient and adaptive soil systems for civil engineering applications. Fig. 1 shows the mechanism of action at the nanoscale in soil.

Fig. 2 presents a heatmap that visually compares the functional performance of four key nanomaterials—Nano-silica, Nano-clay, Carbon Nanotubes (CNTs), and Graphene

Oxide—across five essential soil engineering parameters: Strength, Hydraulic Conductivity, Plasticity Reduction, Durability, and Environmental Safety. Cells are shaded according to performance scores on a 1–10 scale, with darker

shades representing greater effectiveness. Nano-silica exhibits superior performance in terms of strength enhancement and durability, attributed to its cementitious and pozzolanic properties that contribute to the densification of the soil

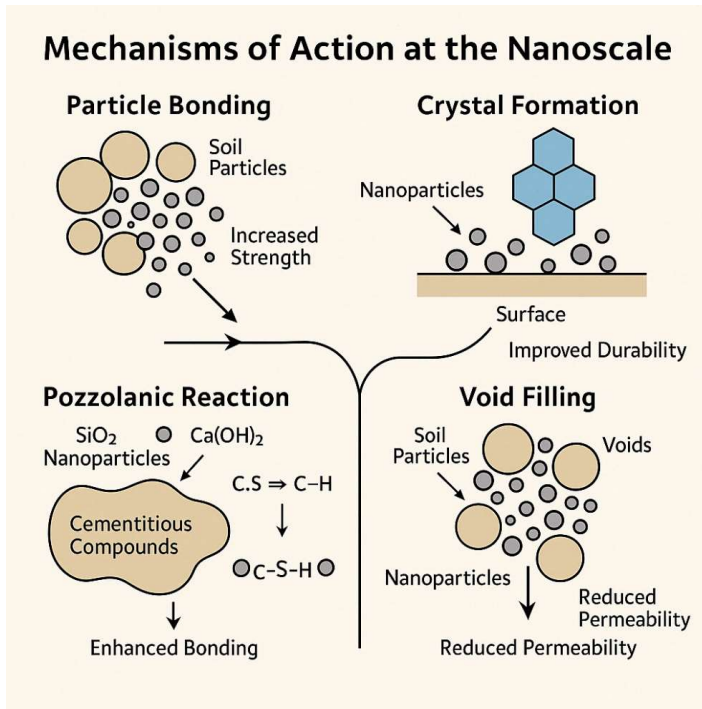


Fig. 1: Mechanism of actions at the nanoscale in soil.

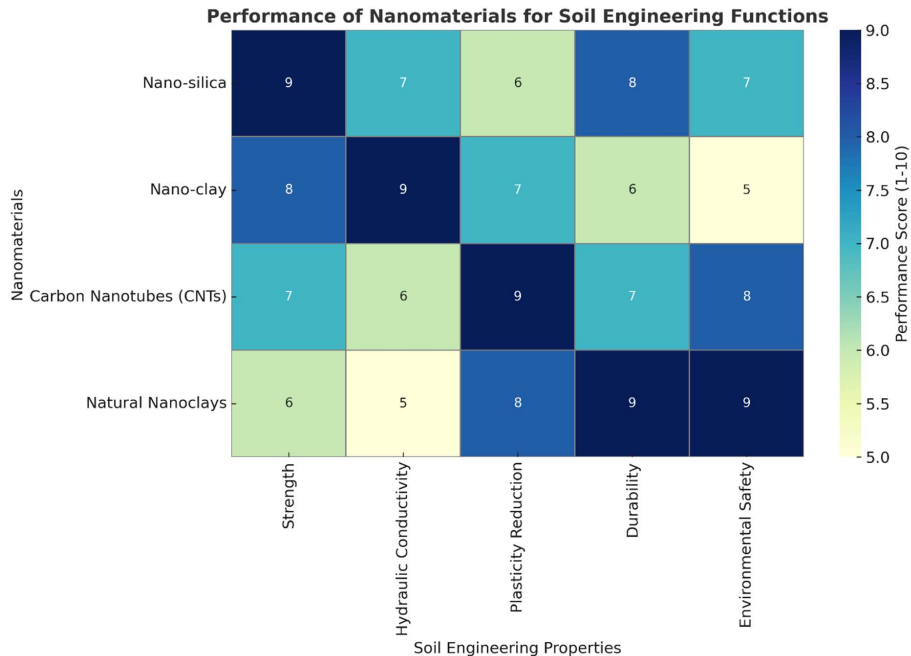


Fig. 2: Performance of nanomaterials for soil engineering functions.

matrix. Nanoclay exhibits optimal performance in controlling hydraulic conductivity and reducing plasticity, rendering it appropriate for impermeable barriers and stabilization of expansive soils. Carbon Nanotubes are notable for their mechanical reinforcement and exceptional durability; however, their environmental safety rating is relatively lower due to concerns regarding bioaccumulation. Fig. 2 shows the performance of nanomaterials in soil engineering.

Development Timeline of Nanotechnology in Geotechnical Engineering (2003–2025)

The timeline figure captures the key advancements in the application of nanotechnology within geotechnical engineering, spanning over two decades of progressive development.

2003 – Early Laboratory Studies on Nano-silica

Research on nano-silica marked the beginning of nanotechnology in soil engineering, focusing on its pozzolanic activity, microstructural refinement, and ability to enhance the compressive strength and shear resistance of treated soils.

2006 – Nano-clay for Swell Control in Expansive Soils

Nano-montmorillonite and similar clay-based nanomaterials gained attention for their role in reducing soil swelling, improving volume stability, and controlling water movement in problematic fine-grained soils.

2010 – CNTs for Stress-Strain Sensing in Geomaterials

The integration of carbon nanotubes (CNTs) has introduced new possibilities in smart soil systems, enabling embedded stress-strain monitoring owing to their excellent conductivity and mechanical reinforcement potential.

2013 – Nano Iron Oxide for Soil Remediation

Nano iron oxide particles were explored for the in-situ treatment of contaminated soils, offering high reactivity and surface area for the removal of heavy metals and organic pollutants through redox reactions.

2015 – Smart Sensors for Real-Time Monitoring

The deployment of smart sensors embedded with nanomaterials in slopes and foundations allows for continuous geotechnical monitoring, capturing parameters such as pore pressure, strain, and deformation in real time.

2018 – Graphene Oxide for Reinforcing Weak Soils

Graphene oxide, known for its exceptional strength-to-weight ratio and surface functionality, was applied to improve the shear strength and ductility of soft or loose soils.

2022 – AI-Assisted Optimization of Nano-Engineered Soil Layers

The combination of artificial intelligence (AI) with nanomaterial-enhanced designs enables data-driven optimization of soil stabilization techniques, supporting customized solutions based on site-specific conditions.

2025 – Widespread Integration of AI and Nanotechnology in Geotech

Looking forward, geotechnical systems are projected to fully embrace AI-integrated nano-engineered materials, leading to the development of intelligent, self-adaptive, and sustainable ground improvement strategies.

Fig. 3: shows the development timeline of nanotechnology in geotechnical engineering from 2003 to 2025.

Nano Materials

Table 1 presents a comparative assessment of four widely

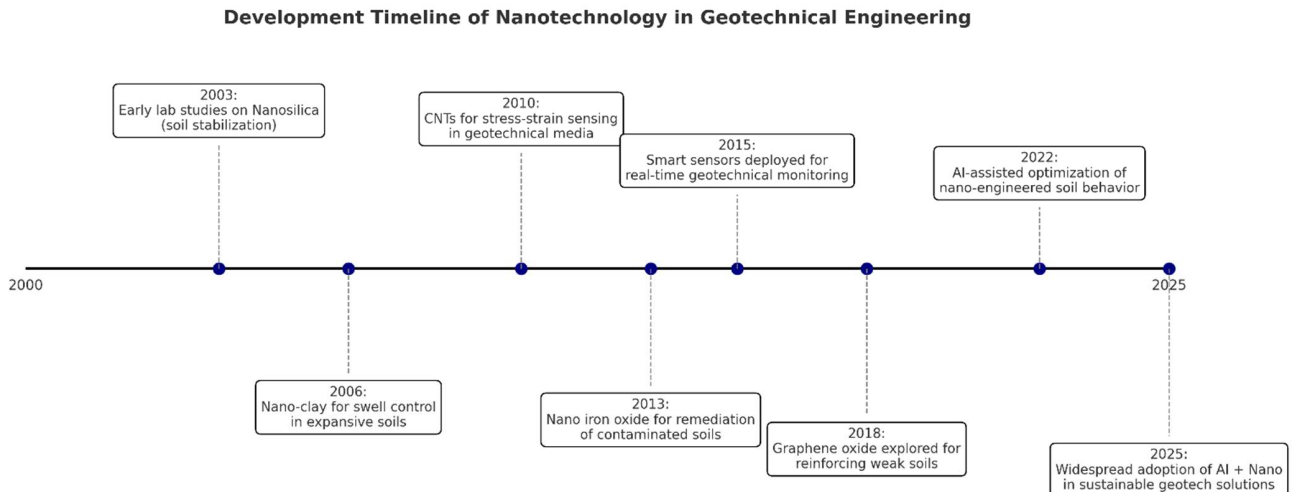


Fig. 3: Development Timeline of Nanotechnology in Geotechnical Engineering (2003–2025).

Table 1: Performance Comparison of Nanomaterials.

Material	Wet Clays	Dry Sands	Expansive Soils	Loose Sands	Contaminated Soils
Nano-silica	7	9	8	9	7
Nano-clay	9	6	9	6	8
Carbon Nanotubes (CNTs)	6	8	7	8	6
Graphene Oxide (GO)	7	8	7	8	9

used nanomaterials—Nano-silica, Nano-clay, Carbon Nanotubes (CNTs), and Graphene Oxide (GO)—across five typical geotechnical soil conditions: *Wet Clays*, *Dry Sands*, *Expansive Soils*, *Loose Sands*, and *Contaminated Soils*. Each material was rated on a performance scale of 1 to 10, with 10 indicating the highest effectiveness, based on parameters such as strength improvement, permeability control, compatibility with soil type, and environmental stability.

Key Insights:

- Nano-silica demonstrated excellent performance in dry and loose sands (score: 9) owing to its strong pozzolanic activity, which densifies granular soils. It also performed well in expansive soils (score: 8) but was moderately effective in wet clays and contaminated soils.
- Nano-clay is most effective in wet clays and expansive soils (score: 9), thanks to its layered structure and water retention capacity. It is particularly suitable for impermeable liners and moisture-sensitive soils but is less effective in dry sand.
- Carbon Nanotubes (CNTs) show strong mechanical performance in dry sands and loose sands (score: 8), enhancing load distribution and tensile strength. However, their performance is moderate to low in wet clays and contaminated soils, where dispersion and potential toxicity are a concern.
- Graphene Oxide (GO) balances mechanical reinforcement and environmental safety. It performs well in contaminated soils (score: 9) due to its high adsorptive capacity and consistently moderate to high scores (7–8) across other soil types, making it a versatile choice

Nano-silica

Nano-silica (SiO_2) is a significant nanomaterial in geotechnical engineering, attributed to its distinctive physicochemical properties, such as fine particle size (generally between 10 and 80 nm), elevated surface area, high reactivity, and pronounced pozzolanic behavior. This effectiveness in modifying the behavior of diverse soil types is particularly enhanced when combined with traditional

stabilizing agents such as cement, lime, and fly ash (Changizi & Haddad 2023, Bayat 2025, Chaudhary et al. 2024, Harsh et al. 2023). Nano-silica enhances soil performance primarily by reacting with calcium hydroxide ($\text{Ca}(\text{OH})_2$), which is a byproduct of cement hydration. This reaction produces more calcium silicate hydrate (C-S-H), a gel-like substance that binds soil particles and enhances the strength of the soil cement matrix. The enhanced production of C-S-H leads to a denser microstructure, better particle bonding, and a significant increase in the unconfined compressive strength (UCS), shear strength, and stiffness modulus of the treated soils.

The effectiveness of nano-silica in soil stabilization is influenced by factors such as soil type, concentration and dispersion of nano-silica, application method (dry mixing versus slurry), and curing conditions (moisture content, temperature, and duration). Uniform dispersion is essential, failure to achieve this may result in agglomeration, leading to inconsistent performance. Researchers have investigated the combined application of nano-silica with various additives, including nano-alumina, polypropylene fibers, and enzymes, to improve the mechanical and hydraulic properties (Bayat 2025, Asad et al. 2024, Dheyaaldin et al. 2022b, Dheyaaldin et al. 2022a).

Nano Clay

Nano-clay, a category of nanomaterials sourced from naturally occurring clay minerals like montmorillonite, kaolinite, and halloysite, has garnered considerable interest in geotechnical engineering due to its capacity to improve the physicochemical and mechanical properties of soil at the nano-scale. Nano-clays are produced via exfoliation or milling processes that decrease particle size to the nanometer scale (generally under 100 nm in at least one dimension), significantly enhancing their surface area and reactivity. The characteristics of nano-clays facilitate enhanced interactions with soil particles, water molecules, and binding agents, leading to significant improvements in soil behavior, especially in stabilization, lining systems, and environmental applications (Das et al. 2023, Harraz 2016).

Nanoclays demonstrate significant adsorption capabilities in environmental applications, which can be attributed to their layered structure and extensive surface area (Awasthi

et al. 2019, Uddin et al. 2024). They effectively immobilize heavy metals, organic pollutants, and radionuclides, rendering them valuable for remediating contaminated soils and groundwater. Engineered modified nanoclays, such as organo-nanoclays, have been designed to specifically target pollutants, thereby improving their application in geotechnical and environmental engineering. Modified clays are used in permeable reactive barriers (PRBs) and soil washing systems for site remediation and groundwater treatment.

Carbon Nanotubes (CNTs)

Carbon Nanotubes (CNTs) are cylindrical nanostructures formed from rolled sheets of graphene, characterized by diameters in the nanometer range and lengths extending to several micrometers. They are classified as single-walled carbon nanotubes (SWCNTs) or multi-walled carbon nanotubes (MWCNTs) based on the number of graphene layers. Carbon nanotubes (CNTs) exhibit exceptional mechanical, electrical, and thermal properties, including high tensile strength (100 times that of steel), light weight, remarkable flexibility, and superior conductivity. Consequently, they have emerged as highly promising materials in the fields of nano-engineered soils and geotechnical engineering. (Gupta et al. 2019, Popov 2004, Zulhairun et al. 2019).

In geotechnical applications, carbon nanotubes (CNTs) are used to improve the mechanical properties of soil, particularly when combined with binders such as cement, lime, or fly ash. The ultra-high aspect ratio of CNTs facilitates the bridging of soil particles and filler matrices, resulting in enhanced interfacial bonding and a denser microstructure (Gupta et al. 2019, Popov 2004). When adequately distributed within soil-cement matrices, carbon nanotubes serve as nano-reinforcement elements, enhancing the unconfined compressive strength (UCS), flexural strength, and ductility. This is especially advantageous in road subgrades, foundations, and embankments, where increased load bearing capacity and durability are critical. A significant benefit of carbon nanotubes (CNTs) in soil systems is their ability to arrest cracks (Saafi et al. 2013, Wong et al. 2020, Chen et al. 2023).

Soils with sensors are critical for early warning systems for slope stability, landslide surveillance, and foundation settlement assessments. CNT-based soil sensors can be embedded in geotextiles or retaining structures to monitor subsurface conditions, allowing for preventative responses or maintenance operations before catastrophic breakdowns occur (Saafi et al. 2013, Wong et al. 2020, Chen et al. 2023).

Graphene and Graphene Oxide (GO)

Graphene and Graphene Oxide (GO), derivatives

of carbon, are increasingly recognized as advanced nanomaterials in geotechnical engineering, attributed to their exceptional mechanical, chemical, and electro-conductive properties. Graphene is a two-dimensional structure consisting of a single layer of carbon atoms organized in a hexagonal lattice. It demonstrates exceptionally high tensile strength (exceeding 100 times that of steel), remarkable thermal and electrical conductivity, and a substantial specific surface area. Graphene oxide is a chemically modified form of graphene that contains various oxygen-containing functional groups, including hydroxyl, epoxy, and carboxyl groups. These modifications enhance its dispersibility in aqueous solutions and improve its chemical reactivity with soil matrices (Yu et al. 2020, Li et al. 2021, Farjadian et al. 2020).

Graphene-based materials enhance soil performance primarily by affecting hydration reactions in cement-stabilized soils (Vasconcelos 2024, Ling et al. 2022, Ji et al. 2022). Graphene oxide, due to its oxygenated functional groups, serves as a nucleation site for the formation of cement hydration products such as calcium silicate hydrate (C-S-H), thereby facilitating accelerated and more comprehensive reactions. This results in enhanced early age strength and decreased porosity, thereby increasing the soil resistance to water infiltration, shrinkage, and freeze-thaw degradation. In addition to their mechanical advantages, graphene and graphene oxide are particularly well-suited for developing smart, sensor-integrated soil systems owing to their superior electrical conductivity.

The adsorptive capacity of GO renders it an effective material for environmental remediation applications. GO sheets can capture and immobilize various contaminants, such as heavy metals (e.g., Pb^{2+} , Cd^{2+} , and Hg^{2+}), organic pollutants (e.g., dyes and pesticides), and radionuclides, owing to their numerous functional groups and strong affinity for these pollutants. Graphene oxide is a promising candidate for the in situ treatment of contaminated soils, landfills, and groundwater barriers. The performance of pollutant adsorption frequently surpasses that of traditional materials, attributed to its capacity to penetrate micropores and establish stable complexes with contaminants. Notwithstanding these benefits, numerous obstacles persist in the extensive implementation of graphene-based materials in geotechnical engineering. Cost remains a significant factor; graphene and GO continue to be relatively expensive to produce, although recent advancements in green synthesis and large-scale production have contributed to cost reduction. Moreover, uniform dispersion within soil matrices is essential for optimal performance, as the agglomeration of graphene sheets may impede their functionality (Baig et al. 2018, Zeinedini and Shokrieh 2024). Surface modification,

sonication, and the application of dispersing agents are frequently utilized to address this issue.

Smart Materials

Smart materials respond to environmental stimuli, including stress, temperature, and damage, rendering them particularly significant in dynamic soil-structure interactions. Piezoelectric sensors are used in foundations, slopes, and embankments for real-time monitoring of stress and strain. The capacity to produce electrical signals in response to mechanical stress facilitates the ongoing evaluation of structural integrity. Shape Memory Alloys (SMAs) can revert to a predetermined configuration upon exposure to designated temperature thresholds. Shape memory alloys (SMAs) are used in geotechnical applications for self-adjusting reinforcement systems, including soil nails and anchors, thereby enhancing the resilience of retaining structures and areas susceptible to landslides. Self-healing materials are integrated into soil-cement or concrete-soil matrices, enabling the autonomous sealing of microcracks using embedded healing agents. This enhances the long-term durability and minimizes maintenance requirements. Fig. 4 illustrates the diverse and emerging roles of smart materials in geotechnical engineering.

Piezoelectric Materials

Piezoelectric materials are advanced materials that produce an electric charge when subjected to mechanical stress and,

in turn, undergo deformation when an electric field is applied (Mahapatra et al. 2021). The distinct electromechanical coupling renders them suitable for application in sensing and actuation systems, particularly in geotechnical engineering, where real-time monitoring of soil behavior is essential for maintaining structural safety and sustainability. Incorporating piezoelectric materials into nano-engineered soils enhances the development of intelligent, responsive, and self-monitoring ground systems.

Embedding piezoelectric sensors within soil matrices or geosynthetic reinforcements, such as geotextiles or geogrids, enables engineers to continuously monitor the mechanical responses of soil in real time. These materials generate electrical signals under stress, eliminating the need for external power supplies (Ju et al. 2023, Gu et al. 2024a).

Lead zirconate titanate (PZT) is a widely used piezoelectric material in geotechnical applications, owing to its high piezoelectric coefficient and consistent performance. Environmentally friendly alternatives such as barium titanate (BaTiO_3) and polyvinylidene fluoride (PVDF) are being increasingly investigated for sustainable applications, especially in sensitive environments like embankments near water bodies, landfill caps, or beneath green infrastructure systems (Tiwari et al. 2021, Berlincourt, 1981).

In nano-engineered soil systems, piezoelectric materials can serve multiple roles.

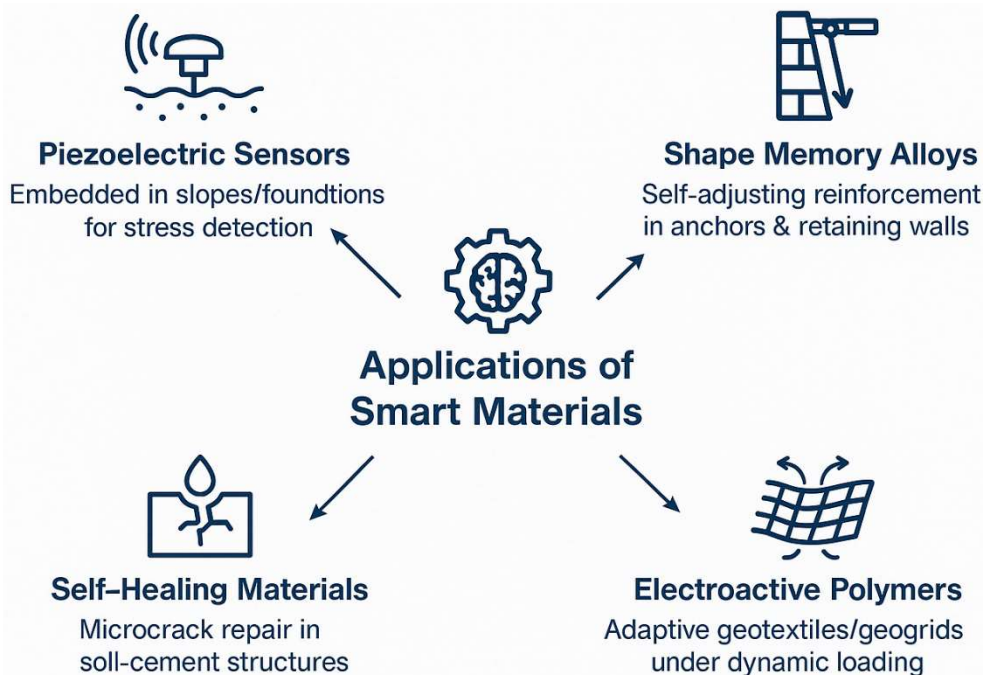


Fig. 4: Diverse and emerging roles of smart materials in geotechnical engineering.

1. **Structural Health Monitoring (SHM):** Piezoelectric sensors identify subtle variations in soil stress, strain, or displacement. For instance, when implemented in slopes or embankments, these sensors can detect micro-deformations and transmit early warning signals prior to the occurrence of macroscopic failure. This proactive capability can substantially mitigate risks and facilitate timely maintenance.
2. **Seismic and Vibration Sensing:** Piezoelectric elements embedded in soil layers exhibit rapid responses to dynamic loading and function as seismographs or vibration detectors. They can capture data during construction activities, traffic-induced vibrations, and natural earthquakes.
3. **Energy Harvesting Systems:** Piezoelectric materials have significant potential for energy harvesting. In areas with high traffic, the mechanical vibrations generated by vehicles can be harnessed to produce electricity through piezoelectric soil beds, supplying energy to low-power sensors or wireless data transmission units, thereby enhancing self-sustaining geotechnical monitoring systems.
4. **Actuation and Control:** Advanced piezoelectric systems can be employed to actively alter the soil behavior. For example, the application of controlled electric fields can enable embedded piezoelectric actuators to modify soil stiffness or induce vibrations to densify loose granular soils, representing a novel approach for active ground improvement.
5. **Moisture and Settlement Detection:** Piezoelectric sensors can detect changes in electrical output resulting from variations in soil stiffness or saturation, offering insights into moisture migration, liquefaction potential, and differential settlement, which are particularly significant for foundations and underground structures.

Shape Memory Alloys

Shape Memory Alloys (SMAs) are a category of advanced materials characterized by their unique capacity to deform and subsequently revert to their initial configuration upon exposure to designated thermal stimuli (Rao et al. 2015, Naresh et al. 2016, Jani et al. 2014). This phenomenon is caused by a reversible solid-state phase transition between the martensite and austenite phases of NiTi. The predominant shape memory alloys are nickel-titanium alloys (NiTi or Nitinol) owing to their remarkable fatigue strength, corrosion resistance, biocompatibility, and ability to recover form.

Shape memory alloys (SMAs) are primarily used in engineered soils to reinforce retaining structures, embankments and slopes. SMAs provide adaptable

reinforcement when mixed with soil or used in conjunction with other geosynthetics. Shape memory alloy (SMA) rods or tendons used in deep foundations or ground anchors may deform under seismic strain and revert to their original shape when heated by friction or an externally provided current that produces a phase transition. The self-healing property is useful for reducing permanent displacement in pile foundations, earth-retaining walls, and tunnel linings after seismic events (Billah et al. 2022, Andrawes 2024, Alam et al. 2007).

The use of sensor technologies and wireless communication systems enhances the real-time monitoring and control capabilities of SMA-embedded soil systems. Integrating shape memory alloys (SMAs) into soil matrices, foundations, or reinforcement layers enables geotechnical engineers to develop self-regulating infrastructure that enhances safety, extends service life, and reduces maintenance requirements. The utilization of shape memory alloys in nano-engineered soil systems represents a novel convergence of materials science and geotechnical engineering, advancing the goals of sustainable and intelligent infrastructure development (Abavisani et al. 2021, Kumar & Ranjan 2025, Tabrizikahou et al. 2022, Abedi et al. 2023).

Electroactive Polymers (EAPs)

Electroactive Polymers (EAPs) are a notable category of smart materials that experience substantial alterations in shape or size upon exposure to electrical stimulation (Rahman et al. 2021, Bar-Cohen and Anderson 2019, Guarino et al. 2016). Their distinct electromechanical coupling behavior enables their use as actuators, sensors, and energy harvesters.

The potential applications of EAPs in nano-engineered soils include the advancement of adaptive foundations and retaining structures (Sohni et al. 2018). Embedded in geosynthetic layers like electroactive geotextiles, EAPs can actively respond to variations in stress, strain, or moisture by modifying their stiffness or geometry

Environmental Assessment Protocols (EAPs) may serve as dynamic sensors within soil systems (Alici et al. 2008, Wang et al. 2016). Their capacity to identify mechanical or electrical changes renders them suitable for the real-time monitoring of deformation, pore pressure variations, or soil settlement. EAPs can also be used to increase the electro-osmotic flow for pollution removal or soil dewatering.

Electroactive polymers (EAPs) can convert mechanical strain from wind, seismic activity, or car vibrations into usable electrical energy for energy-harvesting applications. This capability facilitates the creation of self-sufficient geotechnical monitoring systems, particularly in isolated or off-grid areas. The collected energy can be stored to power

wireless communication modules, convey sensor data, or activate other smart material components inside the system. The soft and elastic characteristics of EAPs enhance their compatibility with soil matrices compared to conventional rigid sensors or actuators.

Self-Healing Materials in Geoenvironmental Soils

Self-healing materials signify significant progress in the creation of sustainable and resilient geotechnical systems (Okem et al. 2024, Dallaev 2024, Al-Tabbaa & Harbottle 2015). Drawing inspiration from biological systems capable of autonomous repair, these materials can inherently detect and rectify microcracks, fissures, or structural degradation without external assistance.

Self-healing can be induced in soil-based materials through several mechanisms. Encapsulated healing agents represent a prevalent method that incorporates microcapsules or hollow fibers containing healing substances, including epoxy, polyurethane, and silica-based gels, within soil-cement composites. When a crack forms, the capsules rupture, releasing the healing agent into the void. Exposure to moisture, air, or catalytic agents induces polymerization or chemical bonding in the healing compound, thereby sealing cracks. This method has demonstrated efficacy in restoring strength and impermeability in stabilized soils and

cementitious ground improvement systems (Qi et al. 2024, Souradeep & Kua 2016, Harbottle et al. 2014, Al-Tabbaa & Harbottle 2015).

Microbial Induced Calcite Precipitation (MICP) is a bio-mediated self-healing process that utilizes bacteria, primarily *Sporosarcina pasteurii*, to precipitate calcium carbonate in response to environmental changes. These microorganisms are either directly integrated into the soil matrix or enclosed within protective shells. In the presence of water or nutrients, bacteria activate a biochemical reaction that leads to calcite formation, filling microcracks or pore spaces of the concrete. MICP offers significant advantages for environmentally sustainable soil stabilization, including enhanced stiffness, decreased permeability, and prolonged durability (Liu et al. 2024, Chang et al. 2024, Zhang et al. 2024, Zhang et al. 2023).

Shape Memory Polymer Capsules: These sophisticated capsules utilize polymers that undergo shape transformation when exposed to external stimuli, such as temperature or moisture. Upon crack formation, these intelligent capsules undergo deformation to release the healing agent or actively expand to seal the gap (Qi et al. 2024, Souradeep & Kua 2016). This method facilitates precise healing with enhanced control and efficiency, which is particularly beneficial in

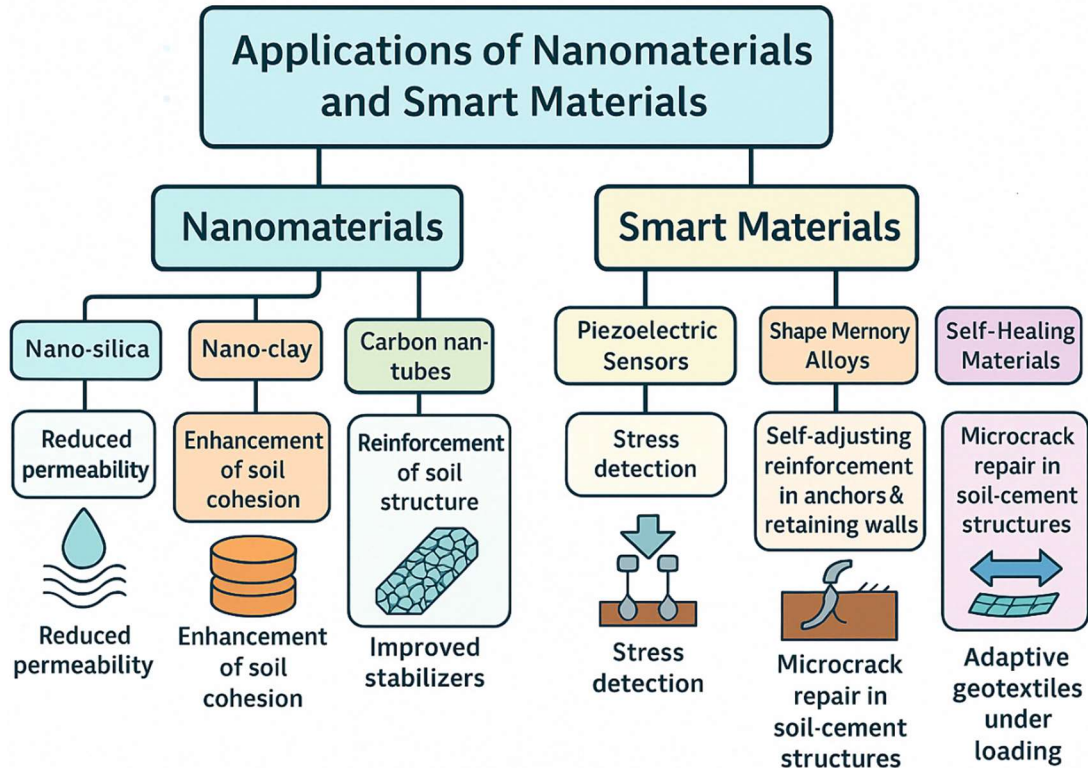


Fig. 5: Applications of nano material and smart materials in geotechnical engineering.

dynamic soil conditions or regions subjected to frequent loading and unloading cycles.

Self-healing materials in geoen지니어ed soils offer numerous benefits. They enhance the longevity and resilience of geotechnical structures by effectively mitigating crack growth and damage progression (Chang et al. 2024, Zhang et al. 2024). Furthermore, they enhance sustainability by minimizing the need for regular maintenance, repairs, and resource-demanding interventions. In environmentally sensitive applications, including landfills, contaminated site containment, and groundwater protection, self-healing barriers are essential for maintaining hydraulic integrity, preventing contaminant leakage, and ensuring long-term environmental safety. From a nanotechnological perspective, nanoscale additives can improve the self-healing efficiency. Nano-silica or nano-clay particles serve as nucleation sites for healing reactions and enhance the dispersion and efficacy of the encapsulated healing agents.

CURRENT APPLICATIONS OF NANO MATERIALS AND SMART MATERIALS IN GEOTECHNICAL ENGINEERING

The application of nanomaterials and smart materials in geotechnical engineering has introduced new opportunities for improving soil performance, stability, and real-time monitoring capabilities (Zhang et al. 2020, Dhattrak & Kolhe 2022, Biswal & Swain 2020, Harsh et al. 2023). Fig. 5 illustrates the utilization of nanomaterials and smart materials within the field of geotechnical engineering

Applications of Nanomaterials and Smart Materials in Soil Stabilization and Reinforcement

The incorporation of nanomaterials and smart materials in geotechnical engineering has initiated advancements in soil stabilization and reinforcement techniques, providing improved mechanical, chemical, and functional properties that exceed those of conventional approaches (Zhang et al. 2020, Majeed & Taha 2013, Biswal & Swain 2020). The application of nanomaterials in soil stabilization is notable for their capacity to enhance soil strength, stiffness, and durability at low dosages. Nano-silica (SiO_2) is commonly used to stabilize expansive and loose soils. When combined with cement or lime, nano-silica improves pozzolanic reactions and occupies micropores in the soil matrix, leading to a denser, more cohesive structure characterized by enhanced unconfined compressive strength and decreased permeability. Nanoclay particles are utilized in fine-grained soils to enhance water retention and mitigate shrink-swell behavior, thereby rendering them appropriate for liners and containment systems. Their elevated surface area and

reactivity further enhance cohesion while diminishing the plasticity.

Carbon nanotubes (CNTs) and graphene derivatives have been employed as next-generation additives for mechanical reinforcement (Ahmad et al. 2015, Islam et al. 2022). These materials, recognized for their exceptional tensile strength and electrical conductivity, are being investigated for the development of multifunctional soil composites that provide mechanical stability and function as strain-sensing elements for early warning systems. The integration of these materials into synthetic geotextiles or soil-cement matrices enhances the load-bearing capacity and crack resistance, especially in high-performance applications, including pavements, foundations, and embankments. Smart materials, alongside nanomaterials, are increasingly recognized for their effectiveness in soil reinforcement, which is attributed to their responsive behavior to environmental stimuli. Piezoelectric materials are embedded in geotextiles and foundation systems to monitor ground vibrations, soil movement, and stress fluctuations in real-time.

Applications of Nanomaterials and Smart Materials in Sensing and Monitoring of Soil

The integration of nanotechnology and smart materials has markedly improved geotechnical sensing and monitoring, allowing engineers to transition from reactive to proactive infrastructure management. Nanomaterials and smart materials are increasingly being integrated into infrastructures and subsurface environments to provide real-time, precise, and intelligent monitoring solutions (Husen & Siddiqi 2023, Das et al. 2015, Sharma et al. 2021). These innovations are significant in essential applications, including slope stability analysis, foundation performance evaluation, ground movement detection, and early warning systems for natural disasters such as landslides and earthquakes.

Applications of Nanomaterials and Smart Materials in Ground Improvement Techniques

The use of nanomaterials and smart materials in ground improvement techniques represents a significant advancement in geotechnical engineering, facilitating improved soil behavior modification, environmental resilience, and adaptive ground responses (Imoni et al. 2023, Huang & Wang 2016). Traditional ground improvement methods, including compaction, grouting, soil replacement, and chemical stabilization, are enhanced by integrating advanced nanomaterials, such as nano-silica, nano-clay, nano-calcium carbonate, and carbon-based nanostructures. These materials enhance the physicochemical interactions among soil particles, resulting in improved load-bearing capacity,

decreased permeability, and increased resistance to erosion and liquefaction. Nano-silica is commonly utilized in lime- or cement-treated soils, as it accelerates pozzolanic reactions, enhances particle binding, and decreases porosity, resulting in a denser and stronger matrix. This method is particularly effective for treating soft clays, loose sands, and expansive soils frequently encountered in infrastructure development.

ENVIRONMENTAL LINKAGES AND SUSTAINABILITY ASPECTS

Advancing responsible innovation necessitates the consideration of sustainability concerns and environmental connections associated with the application of nanomaterials and smart materials in soil engineering. Life Cycle Assessment (LCA) offers a systematic approach to assess the environmental impact of materials throughout their life cycle, from production to disposal, and identifies opportunities to enhance resource efficiency and reduce emissions. Despite these technical advantages, concerns

persist regarding the toxicity and bioaccumulation potential of certain nanoparticles, which, if inadequately managed, could jeopardize human health, groundwater quality, and soil ecosystems. Consequently, scientists are scrutinizing circular economy strategies by developing bio-nanocomposites and environmentally sustainable alternatives that utilize industrial and agricultural waste. The incorporation of these materials into geotechnical systems enhances climate-resilient infrastructure by augmenting longevity, reducing maintenance requirements, and enabling adaptive responses to adverse weather conditions (Tabrizikahou et al. 2021, Wahab et al. 2024, Kumar et al. 2024). These strategies highlight the necessity of balancing technological progress with ecological responsibility in geotechnical engineering.

The radar chart presents a visual comparison of the environmental performance of frequently utilized nanomaterials in geotechnical engineering across five critical dimensions: biodegradability, energy consumption during

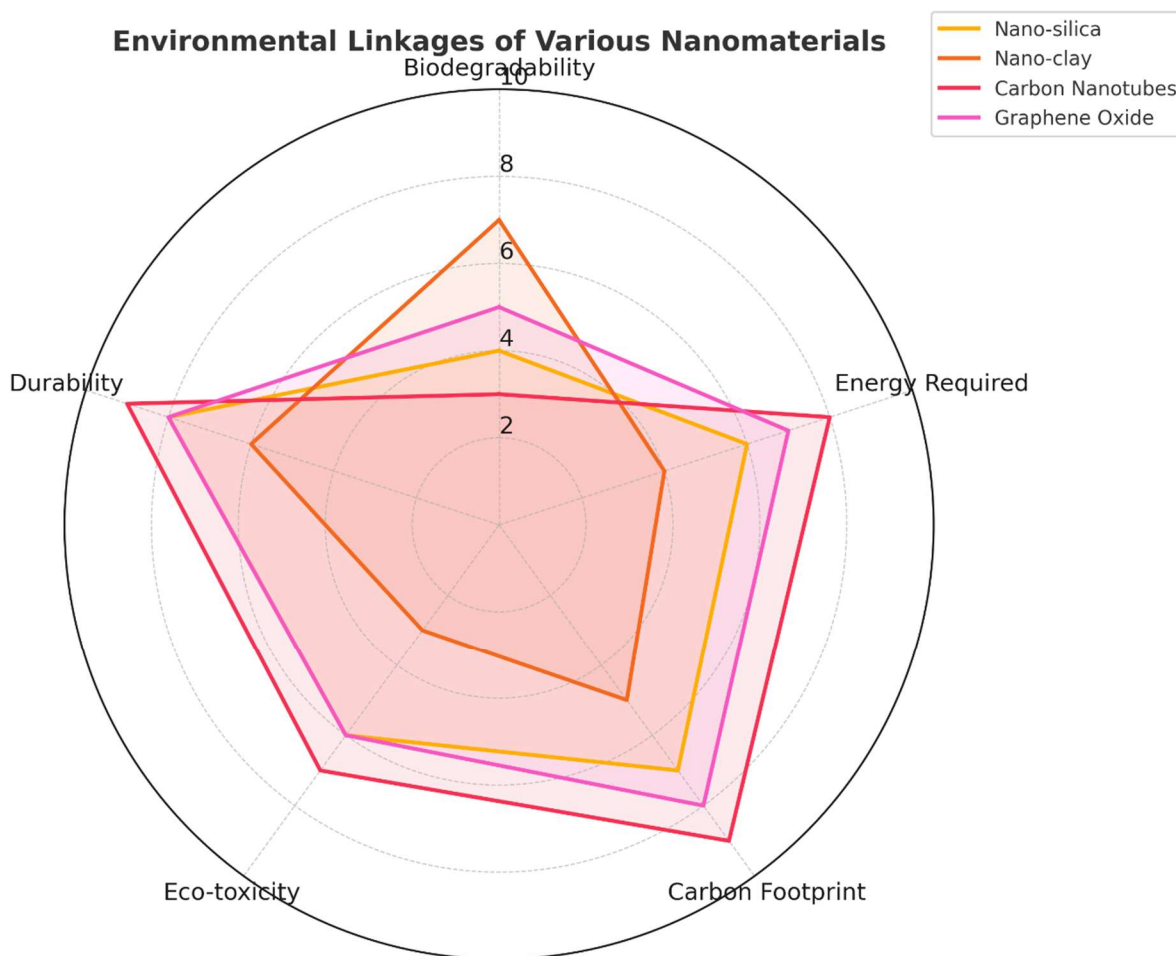


Fig. 6: Environmental linkage of various nanomaterials.

production, carbon footprint, ecotoxicity, and long-term durability. These factors assess both the functionality of nanomaterials and their sustainability and ecological impact throughout their life cycles.

Fig. 6 indicates that nanoclay possesses a balanced environmental profile characterized by high biodegradability, low ecotoxicity, and minimal energy consumption, rendering it suitable for sustainable soil enhancement. Nano-silica demonstrates high durability but exhibits lower biodegradability and requires moderate energy consumption. Carbon nanotubes (CNTs) exhibit significant durability, however, they present issues related to high production energy, an increased carbon footprint, and potential bioaccumulation, which diminish their environmental advantages. Graphene oxide presents a balanced profile, demonstrating superior eco-safety compared to carbon nanotubes while also showing potential for effective long-term applications. Fig. 6 facilitates the selection of nanomaterials by incorporating both technical efficiency and eco-conscious engineering considerations into contemporary geotechnical practice.

SMART MATERIALS PERFORMANCE MATRIX IN SOIL SYSTEMS

The radar chart offers a comparative analysis of four significant smart materials-Piezoelectric materials,

Shape Memory Alloys (SMAs), Electroactive Polymers (EAPs), and Self-healing composites-evaluated against six performance metrics pertinent to geotechnical applications: responsiveness, energy efficiency, durability, cost, adaptability, and sustainability. Piezoelectric materials demonstrate significant responsiveness and energy efficiency, rendering them appropriate for real-time stress sensing and monitoring in foundations and slopes (Fig. 7). Nonetheless, their adaptability and cost-efficiency are average. Shape memory alloys exhibit remarkable durability and adaptability, especially in applications such as self-adjusting reinforcements, including soil nails and anchors. However, their elevated cost and energy-intensive manufacturing processes impact their sustainability profile. Although EAPs have comparatively low endurance in harsh conditions, their significant plasticity and reactivity point to possibilities in adaptive geosynthetics. Although self-healing composites are suitable for long-term infrastructure due to their considerable sustainability and durability, their reactivity is inevitably restricted to fracture activation.

By balancing innovation, pragmatism, and sustainability in soil systems, this comparative matrix helps engineers select intelligent materials that align with specific functional and environmental goals.

Life Cycle Assessment (LCA) of Nanomaterials and Smart Materials in Soil Engineering

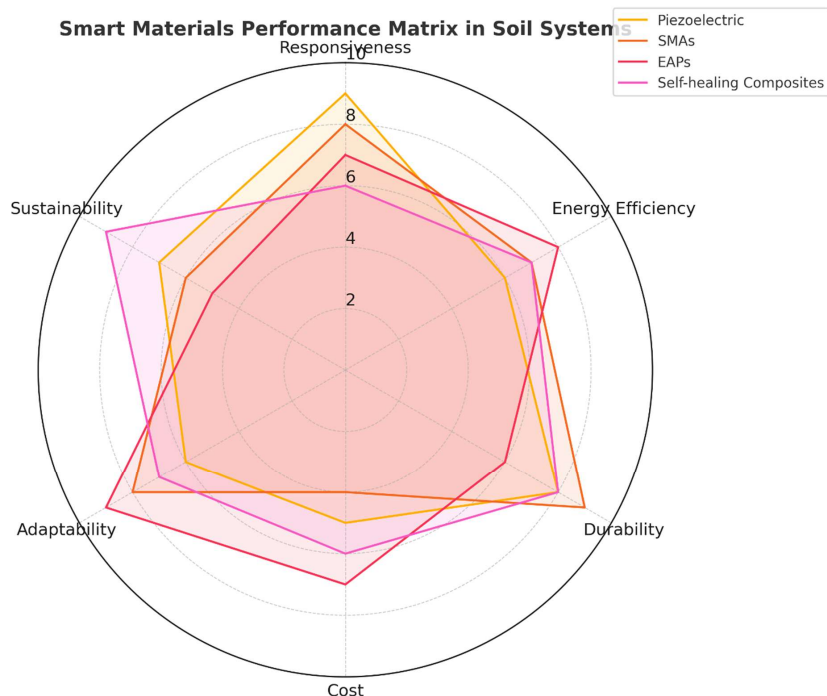


Fig. 7: Smart materials performance matrix in soil systems.

The use of nanomaterials and smart materials in soil engineering methods improves the performance, monitoring capabilities, and durability of geotechnical constructions. As these materials become more prevalent, it is critical to examine their overall environmental impact using systematic methodologies, such as Life Cycle Assessment (LCA). LCA is a comprehensive analytical tool for measuring the environmental implications of all stages of a product's lifecycle, including raw material extraction, production, application, usage, and final disposal. LCA assesses the trade-offs between increased geotechnical performance and potential environmental costs in the context of nanomaterials for ground improvement and soil stabilization (Hischier & Walser 2012, Visentin et al. 2021, Gallagher et al. 2017).

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Nanosilica (Precipitated): LCA case study (China): Renewable electricity (wind, hydro, solar) reduces emissions by 40–90% compared with coal. Sodium carbonate accounts for 40–70% of the impacts in categories such as GWP, acidification, and ecotoxicity (Gu et al. 2024b).

Graphene Production Methods: Ultrasonication reduces energy and water use by ~50% compared to chemical reduction, but human toxicity impact is doubled. In chemical reduction, hydrazine contributes nearly 100% of the toxicity impact (Arvidsson 2017).

Ecotoxicity/Toxicity Indices (TEF, EC50)

ENMs EC50 values are generally in the range of mg/L to mmol/L in aquatic systems.

Silver nanoparticles usually exhibit the highest toxicity. Meta-analysis notes wide variation and lack of consistency in ENM ecotoxicity reporting (Dodds et al. 2021).

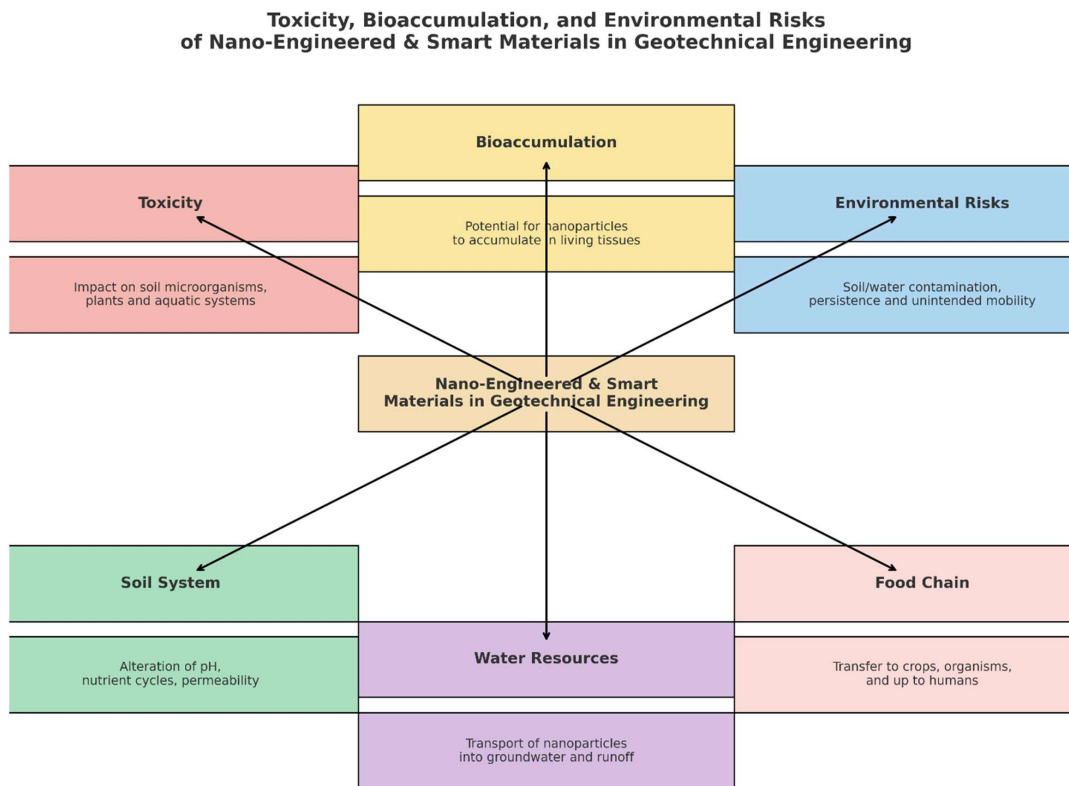


Fig. 8: Toxicity, bioaccumulation, and environmental risks associated with nanomaterial and smart material.

Graphene Flagship Review Highlights lack of standardized EC50 reporting and sparse chronic exposure data across 650+ studies (Lin et al. 2024).

Toxicity, Bioaccumulation, and Environmental Risks

The challenges in monitoring nanoparticles in the environment render the end-of-life phase of nanomaterials one of the most poorly understood aspects of the LCA framework. Enhanced soil strength, real-time sensing, and adaptive behavior are among the performance benefits these materials provide; however, they also present some risks that require meticulous evaluation. The introduction of engineered nanomaterials (ENMs), such as nano-silica, carbon nanotubes (CNTs), nano-titania, and nano-iron oxides, into soil ecosystems raises significant toxicity concerns for soil organisms. These materials may adversely affect plant roots, soil microbes, and groundwater chemistry due to their small size and high surface reactivity. Research indicates that specific nanoparticles can modify soil fertility by influencing the nitrogen and phosphorus cycles, disrupting microbial metabolic pathways, or inhibiting enzyme activity. This microbial perturbation may adversely affect plant growth, soil vitality, and the overall functioning of terrestrial ecosystems (Utsev et al. 2022).

Bioaccumulation is a serious risk, particularly when nanoparticles are left in the environment without being sufficiently broken down. These materials can be assimilated

by soil organisms, including bacteria, fungi, and earthworms, which then incorporate them into the food chain. Long-term exposure may cause accumulation at higher trophic levels, which could have negative effects on the environment and human health. (Deng et al. 2017, Lead et al. 2018, Uddin et al. 2020).

Fig. 8 shows the environmental risks associated with the use of smart and nano-engineered materials in geotechnical applications. The long-term environmental behavior of these materials is a major concern, despite their tremendous advantages in terms of strength, adaptability, and monitoring capabilities.

Responsible innovation, based on thorough environmental assessments and sustainable material design, is essential for optimizing benefits and reducing unintended ecological impacts

Circular Economy Potential and Eco-Friendly Alternatives

The incorporation of nano-engineered and smart materials in geotechnical engineering presents significant opportunities for technical advancement and the integration of circular economy principles in soil enhancement and infrastructure development (Saeli 2011, Kiani 2024, Mohamed 2015). Civil and geotechnical engineering have historically been linked to linear resource consumption models,

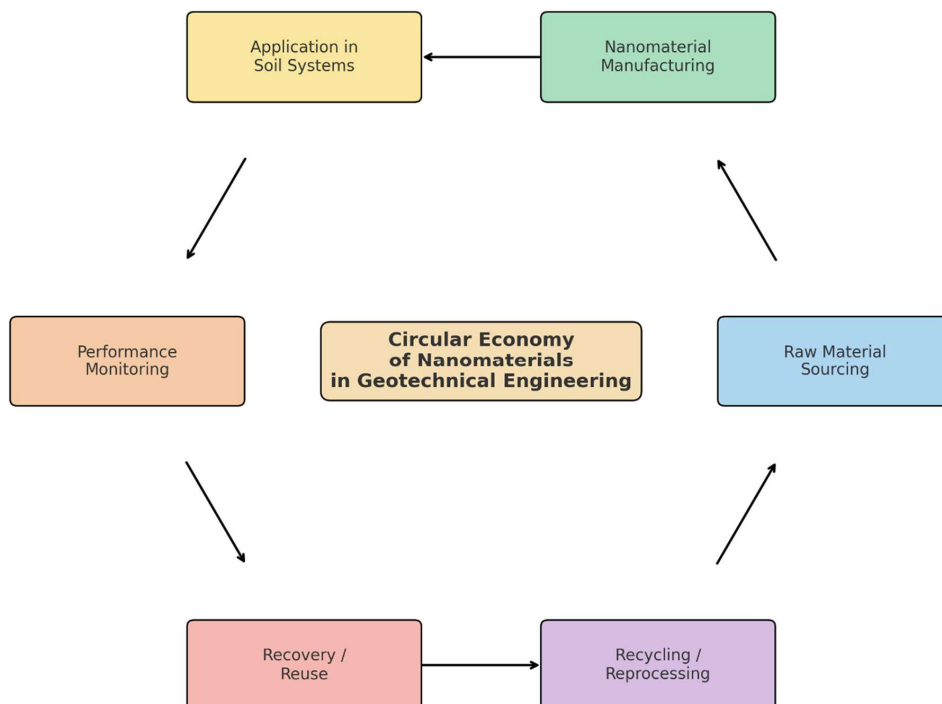


Fig. 9: Circular economy of nanomaterials in the geotechnical field.

characterized by extraction, utilization, and disposal. The emergence of nanomaterials and smart materials facilitates a transition to regenerative practices, wherein materials are engineered for reuse, recyclability, minimal waste generation, and diminished environmental impact. The reuse of industrial by-products and bio-based sources as feedstocks for nanomaterials represents a promising approach. Nano-silica can be synthesized from readily available and underutilized resources such as rice husk ash or waste glass. This approach reduces the demand for virgin materials and diverts agricultural and industrial waste from landfills, thereby supporting a circular economy. Fig. 9 illustrates the circular economy of nanomaterials in the geotechnical field.

The connection between nano-engineered materials and circular economy principles represents a practical approach to enhancing sustainability in soil engineering. Rethinking the sourcing, application, and recovery of these materials allows the geotechnical field to advance intelligent, efficient, environmentally regenerative engineering systems that are aligned with global sustainability objectives (Reddy et al. 2024, Berry et al. 2023, Basu et al. 2015).

Standards and Regulatory Frameworks for Nanomaterials in Geotechnical Applications

As the use of nanomaterials expands within geotechnical

engineering, the absence of clearly defined regulatory protocols, material characterization standards, and field validation guidelines remains a significant barrier to their mainstream adoption. This section outlines the current state of available standards (ASTM, ISO, IS, OECD, USEPA, and REACH) and highlights the gaps where nanomaterial-specific guidance is either lacking or under development.

This section addresses the gaps in the existing standards and regulatory frameworks that govern the integration and testing of nanomaterials in geotechnical and environmental engineering. It provides an overview of the available standards (ASTM, ISO, IS) and identifies critical areas where standards are still lacking. Table 2 outlines the relevant standards and codes governing nanomaterial usage in soils, their environmental implications, and associated testing protocols. It highlights the current coverage and identifies significant regulatory and procedural gaps.

Cost-Performance Comparison of Popular Nanomaterials in Soil Stabilization

Table 3 presents a comparative analysis of three widely used nanomaterials— nano-silica, Carbon Nanotubes (CNTs), and Graphene Oxide (GO)—in terms of their cost-effectiveness when used as soil stabilizers. The table outlines each material's approximate market price, typical dosage range by

Table 2: Summary of Existing and Missing Standards/Regulatory Frameworks for Nanomaterial Integration in Geotechnical and Environmental Applications.

Category	Standard/Code	Coverage Area	Remarks/Gaps
Nanomaterial Characterization	ISO/TR 18196:2016	Measurement techniques for nanomaterial properties	Describes methods but lacks soil-specific guidance
Environmental Leaching	USEPA SW-846 Method 1311 (TCLP)	Toxicity Characteristic Leaching Procedure	Not tailored for engineered nanomaterials
Soil Testing with Additives	ASTM D4609	Soil chemical stabilizers (like lime/cement)	No extension to nanoscale additives
Field Monitoring	ASTM D7757	Real-time sensing using geotechnical instrumentation	No direct linkage to nano-enabled sensors
Toxicity Assessment	OECD Guidelines (e.g., TG 201–203)	Ecotoxicity of chemicals	Limited to aquatic systems, lacks terrestrial protocol for nanomaterials
Regulatory Oversight	EU REACH Regulation	Chemical safety registration and risk assessment	Nanomaterials covered under specific annexes but site-use protocols lacking
India National Standards	IS 2720 (Parts 1–41)	Soil testing procedures	Do not incorporate nano-additive testing provisions
Nanomaterial Safety	ISO/TS 12901-2:2014	Occupational exposure prevention	Pertains to manufacturing, not site use

Table 3: Cost-Performance Comparison of Popular Nanomaterials in Soil Stabilization.

Nanomaterial	Approx. Cost (USD/kg)	Typical Dosage (% by weight of dry soil)	UCS Gain (kPa)	Cost per kPa Strength Gain (USD/kPa)	Remarks
Nano-silica	5–10	1–2%	200–400	~0.025–0.10	High efficiency, good dispersibility
Carbon Nanotubes	100–200	0.05–0.1%	300–600	~0.17–0.33	Excellent reinforcement but costly
Graphene Oxide (GO)	50–100	0.1–0.2%	250–500	~0.10–0.20	Moderate cost, good strength and durability

dry weight of soil, reported unconfined compressive strength (UCS) improvement, and calculated cost per unit strength gain in USD per kPa.

CHALLENGES AND LIMITATIONS

Although advancements in nanomaterials and smart materials for geotechnical engineering are promising, various challenges and limitations hinder their widespread adoption. The primary technical challenge is the difficulty in achieving a uniform dispersion of nanoparticles within soil matrices, which affects their efficiency and performance. The scalability of lab-based innovations to large-scale geotechnical applications presents a significant challenge, which is further complicated by uncertainties related to the long-term behavior and durability of these materials in diverse environmental conditions. The safe use and market acceptance of novel materials are hampered by the absence of standardized testing methods, precise standards, and regulatory frameworks for their use. Cost is a significant barrier, especially in situations with limited resources, where the synthesis, processing, and application of nanomaterials and intelligent components may not be economically feasible for large-scale infrastructure projects. To fully realize the promise of these technologies in influencing soil engineering in the future, these constraints must be addressed (Khatoon & Velidandi 2025).

Dispersion, Scalability, and Long-Term Behaviour

Despite the significant potential of smart and nano-engineered materials in geotechnical engineering, several technical challenges hinder their extensive application. Ensuring uniform dispersion, confirming scalability in production and application, and comprehending their long-term behavior in complex soil environments are critical. A significant difficulty in soil matrices is the proper dispersion of nanoparticles. Robust van der Waals forces induce aggregation of nanomaterials, such as graphene oxide, carbon nanotubes (CNTs), and nano-silica. This aggregation reduces their functional capabilities and surface areas. Achieving homogeneous mixing at the nanoscale in practical field applications is particularly challenging, especially given the variability in soil moisture content, pH, and organic matter levels. Poor dispersion may result in inconsistent performance, with certain soil areas benefiting from reinforcement, while others remain unaffected.

Lack of Standards, Guidelines, and Regulatory Frameworks

Notwithstanding the considerable progress in nanotechnology and smart materials in geotechnical engineering, a

fundamental obstacle remains: the absence of established norms and regulatory frameworks to guarantee their safe, effective, and uniform implementation. Unlike traditional construction materials such as cement, steel, or geotextiles, which adhere to established national and international standards, the application of nanomaterials such as nano-silica, carbon nanotubes, and graphene in soils is marked by the absence of standardized protocols for their characterization, dosage, handling, and performance evaluation. The lack of regulation creates ambiguity for engineers and decision-makers, hindering the incorporation of new materials into conventional designs and construction procedures. In the absence of defined benchmarks for nanoparticle concentration, toxicity thresholds, or allowable leaching levels into groundwater, engineers are compelled to rely on disparate literature or case-specific experiments, thereby increasing the likelihood of technical errors and unforeseen environmental consequences in the remediation process.

Cost and Economic Viability for Large-Scale Applications

The primary obstacles to the broad use of nano-engineered and smart materials in soil engineering are their high cost and uncertain economic viability concerning their production, processing, and large-scale use. Laboratory investigations and pilot-scale applications have shown that nanomaterials have several advantages, including enhanced strength, reduced permeability, and self-sensing capabilities. However, their synthesis and modification are sometimes prohibitively expensive. Complex manufacturing processes that necessitate controlled conditions, specialized equipment, and significant energy investment are required to produce materials such as carbon nanotubes, graphene oxide, and high-purity nano-silica. Owing to their higher production costs, these features render their use in large-scale infrastructure projects economically impractical, as cost-effectiveness is a key concern.

FUTURE POTENTIAL AND RESEARCH DIRECTIONS

Nano-engineered and smart materials have significant potential applications in geotechnical engineering, particularly when combined with advanced and environmentally friendly technologies. Intelligent soil systems that can independently monitor, predict, and respond to geotechnical changes in real time are made possible by the combination of artificial intelligence (AI) and the Internet of Things (IoT). Intelligent networks equipped with nanosensors and adaptive materials can improve infrastructure safety by implementing early warning systems and automated maintenance strategies.

Simultaneously, research is increasingly directed towards the creation of bio-inspired and environmentally friendly nanomaterials sourced from natural or waste resources to mitigate environmental and toxicity issues while preserving engineering efficacy. The transition from laboratory-scale success to practical implementation necessitates extensive field-scale validation and long-term performance monitoring across various climatic and loading conditions. These initiatives will bridge the divide between research and practice while contributing to the development of resilient, adaptive, and eco-efficient geotechnical systems.

Integration with AI and IoT for Smart Soil Systems

A revolutionary development in geotechnical engineering, the combination of nano-engineered and smart materials with cutting-edge technologies like artificial intelligence (AI) and the Internet of Things (IoT) holds out the possibility of creating completely intelligent and adaptable soil systems. Real-time monitoring, prediction, and adaptation to subsurface conditions are required owing to the growing complexity of infrastructure demands caused by urbanization, climate change, and sustainability goals. When integrated into the soil matrix, smart materials such as piezoelectric sensors, shape memory alloys, and electroactive polymers serve as sensory nodes that detect variables such as strain, pressure, moisture content, and temperature changes. By using IoT-enabled devices to network these materials, engineers can establish interconnected geotechnical settings that provide constant streams of data for real-time decision-making.

Bio-Inspired and Green Nanomaterials for Geotechnics

The growing emphasis on sustainability in civil and geotechnical engineering highlights the potential of bio-inspired and green nanomaterials for developing environmentally responsible and resource-efficient ground improvement methods. In contrast to traditional nanomaterials, which typically require energy-intensive production methods and pose ecological risks, bio-inspired nanomaterials are sourced from natural systems, processes, or organisms, emulating the mechanisms of stabilization and self-healing found in nature. These materials are generally biodegradable, non-toxic, and renewable, which aligns with circular economy principles and reduces long-term environmental impact. A notable example in this field is microbially induced calcite precipitation (MICP), in which naturally occurring bacteria facilitate the precipitation of calcium carbonate, thereby binding soil particles, enhancing stiffness, and decreasing permeability. The biomineralization process is augmented by nano-calcium carbonate particles,

which provide high surface activity and fine particle distribution, facilitating more effective bonding.

Field-Scale Validations and Performance Monitoring

Laboratory investigations have demonstrated the potential of nano-engineered and smart materials to improve soil behavior; however, the transition from laboratory-scale studies to real-world field applications remains a significant challenge. Validation at the field scale and monitoring of long-term performance are crucial for determining the practicality, reliability, and robustness of these innovative materials under various environmental and loading conditions. Future research should focus on large-scale trials to evaluate the performance of nanosilica, nanoclays, carbon nanotubes, graphene derivatives, and smart materials, such as piezoelectric sensors and shape memory alloys, in heterogeneous and dynamically changing soil environments. Field studies will verify the repeatability of the performance enhancements, including increased shear strength, reduced settlement, and improved drainage. Additionally, they offer insights into material behavior over extended periods, encompassing aging, degradation, and interactions with soil chemistry.

CONCLUSIONS

The rapid development of nanotechnology and the emergence of smart materials have created significant opportunities in geotechnical engineering. To clarify their definitions, classifications, mechanisms of action, and many uses, this study compiles the most recent data on smart materials and nano-engineered soils. Significant improvements in mechanical and physical characteristics, such as shear strength, stiffness, water retention, and reduced permeability, have been demonstrated by incorporating nanomaterials into soil systems, including graphene, carbon nanotubes (CNTs), nanosilica, nanoclay, and nanocalcium carbonate. Owing to these advancements, nanomaterial-based soil treatments can effectively replace traditional soil stabilization methods, particularly for challenging soils. Geotechnical systems are now dynamic, adaptive entities instead of static ones because of smart materials such as piezoelectric materials, shape memory alloys (SMAs), electroactive polymers, and self-healing composites. These materials can perceive environmental stimuli, such as strain, temperature, or stress, and respond instantly through self-healing or actuation mechanisms. By integrating monitoring and adaptive reactions inside the soil-structure matrix, this presents a novel approach to infrastructure design and maintenance that greatly improves the performance, longevity, and safety of geotechnical assets.

In addition to enhancing performance, smart materials and nanoparticles hold great promise for the development of environmentally friendly engineering methods. Life Cycle Assessment (LCA) studies have begun to clarify how these advanced materials affect the environment, highlighting their potential benefits and risks. The adsorption of heavy metals or other contaminants from contaminated soils is one way in which some nanomaterials, such as nano-alumina and nano-iron oxides, improve environmental remediation. However, some have legitimate concerns regarding toxicity, bioaccumulation, and potential environmental disruption. An important area for future research is the development of ecologically friendly synthesis techniques and sustainable biomimetic substitutes. As infrastructure systems work toward sustainability and climate resilience, the role of these materials in a circular economy—characterized by waste reduction and the recycling or repurposing of resources—is an important area of focus.

Notwithstanding these benefits, several important issues must be resolved before widespread implementation is possible. Significant technical obstacles still exist, including the consistent dispersion of nanoparticles in various soil types, long-term stability and behavior, and scaling from laboratory settings to field applications. The economic feasibility of utilizing high-cost nanomaterials in resource-constrained geotechnical projects restricts their broad-scale implementation. Gaps in regulatory oversight and standardization are significant, currently, there are no universally accepted protocols, performance benchmarks, or safety guidelines for using nanomaterials and smart materials in soils. Overcoming these challenges requires multidisciplinary research collaboration, transparent policy formulation, and efforts toward global standardization. The future of geotechnical engineering lies at the intersection of materials science, digital technologies, and sustainability. The combination of artificial intelligence (AI) and Internet of Things (IoT) platforms with nano-engineered and smart materials may enable the development of fully autonomous and self-regulating geotechnical systems. Smart soil systems can monitor subsurface conditions, predict failures, and respond adaptively, thereby enhancing the intelligence and resilience of infrastructure. The investigation of biocompatible, non-toxic, and renewable nanomaterials derived from natural processes, such as microbial mineralization and plant-based nanocellulose, signifies a sustainable advancement. Robust field-scale studies, long-term monitoring, and real-world case applications should be prioritized to validate and scale these innovations. The integration of nano-engineered soils with smart materials presents significant opportunities for transforming geotechnical engineering by enhancing its intelligence, adaptability, and sustainability. Despite the

presence of technological, environmental, and economic challenges, the future appears promising, propelled by innovation, interdisciplinary collaboration, and a collective global commitment to developing sustainable infrastructure.

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