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Review

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 a crucial field to build, analyze, and study 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, mechanisms of interaction with soil matrices, and further explains their prospective applications in stabilization, reinforcement, sensing, and ground improvement technologies. Widely-used nano-materials like nano-silica, nano-clay, carbon nano tubes, graphene and nano-calcium carbonate have exhibited a 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 upon soil systems adaptive functions and integrated sensing capabilities, enabling realtime monitoring and adaptive behaviour. It also reviews the environmental consequences and sustainability considerations for the implementation of 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 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. Last, the paper concludes with directions for future research, such as necessity for field-scale validations, integration with Artificial Intelligence and Internet of Things technologies for smart soil systems, and formulation of eco-friendly, bio-compatble nanomaterials. This review emphasizes that nano-engineered soils and smart materials can reshape geotechnical engineering and offers forward-looking perspectives of how asset (infrastructure) owners and the construction industry may benefit from resilient, intelligent and sustainable solutions.

1. INTRODUCTION

Geotechnical engineering is the design and building of structures which is a essential subdiscipline of civil engineering, it helps to maintain natural trends and forces with man-made structures when it comes to 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 place to another and even over short spatial distances. Such variations frequently yield erratic performance under loading or externally driven environ-mental changes, which generate geotechnical problems such as excessive settlement, slope failures, liquefaction, expansive soil behaviour 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 failures, making geotechnical dependability an issue of paramount importance in contemporary resilient infrastructure development (Acharya, 2024, Kandalai et al., 2023).

The manipulation of matter at the atomic, molecular, or supramolecular level within the size range of 1 to 100 nanometers is known as nanotechnology, and it has become a revolutionary force in many fields of science and engineering. Nanomaterials have 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 greatly 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 porosity. Because of their high aspect ratio and surface charge, nano-clays help to 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—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 utilized 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 or slopes. Shape memory alloys (SMAs) exhibit the ability to revert to a predetermined configuration when subjected to heat. Their potential applications are being explored in adaptive shoring systems and seismic isolation (Fang and 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, are enhancing the durability of soil-cement or concrete-soil composites by facilitating automatic repair of micro-damage (Kurzekar 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 work is significant due to its comprehensive and interdisciplinary approach. The paper integrates insights from geotechnical engineering, nanoscience, material 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:

SDG 9: Industry, innovation, and resilient infrastructure

SDG 11: Sustainable cities and communities

SDG 13: Climate action

2. Rise of Nanotechnology and Smart Materials in Civil and Geotechnical Engineering

Nanomaterials improve the geotechnical properties of soil by functioning at the micro- to nano-scale within the soil matrix. Upon introduction to the soil, nano-additives like 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 due to pozzolanic activity, wherein nanoparticles react with calcium hydroxide to produce calcium silicate hydrate (C-S-H), thus enhancing the soil's strength and cohesion. In advanced applications, carbon nanotubes (CNTs) are integrated into the soil matrix, creating 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. Figure 1: Shows the Mechanism of Actions at the nanoscale in Soil.

Figure 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 strength enhancement and durability, attributed to its cementitious and pozzolanic properties that contribute to the densification of the soil matrix. Nano-clay exhibits optimal performance in controlling hydraulic conductivity and reducing plasticity, rendering it appropriate for impermeable barriers and the 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. Figure 2 Shows the Performance of Nanomaterials for Soil Engineering Functions.

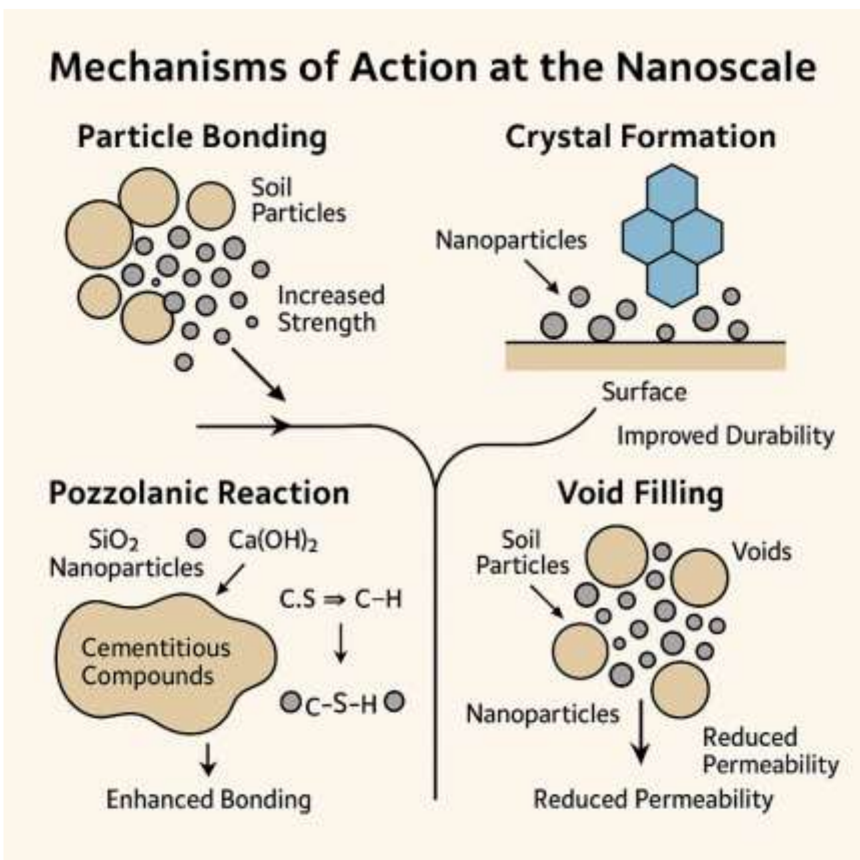

Figure 1: Mechanism of Actions at the nanoscale in Soil

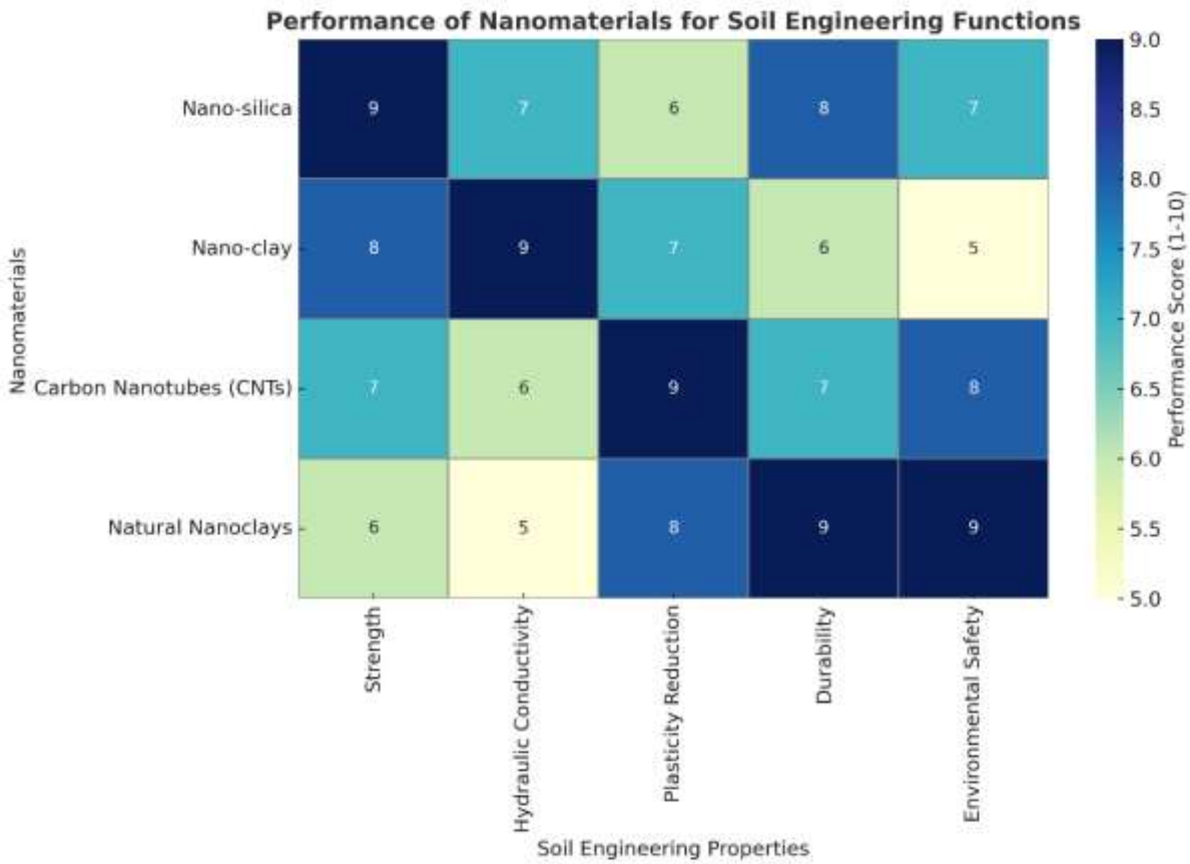

Figure 2 Shows the Performance of Nanomaterials for Soil Engineering Functions.

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 compressive strength and shear resistance in 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) introduced new possibilities in smart soil systems, enabling embedded stress–strain monitoring due 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

Deployment of smart sensors embedded with nanomaterials in slopes and foundations allowed for continuous geotechnical monitoring, capturing parameters like 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 enabled 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. Figure 3: Shows the Development Timeline of Nanotechnology in Geotechnical Engineering (2003–2025)

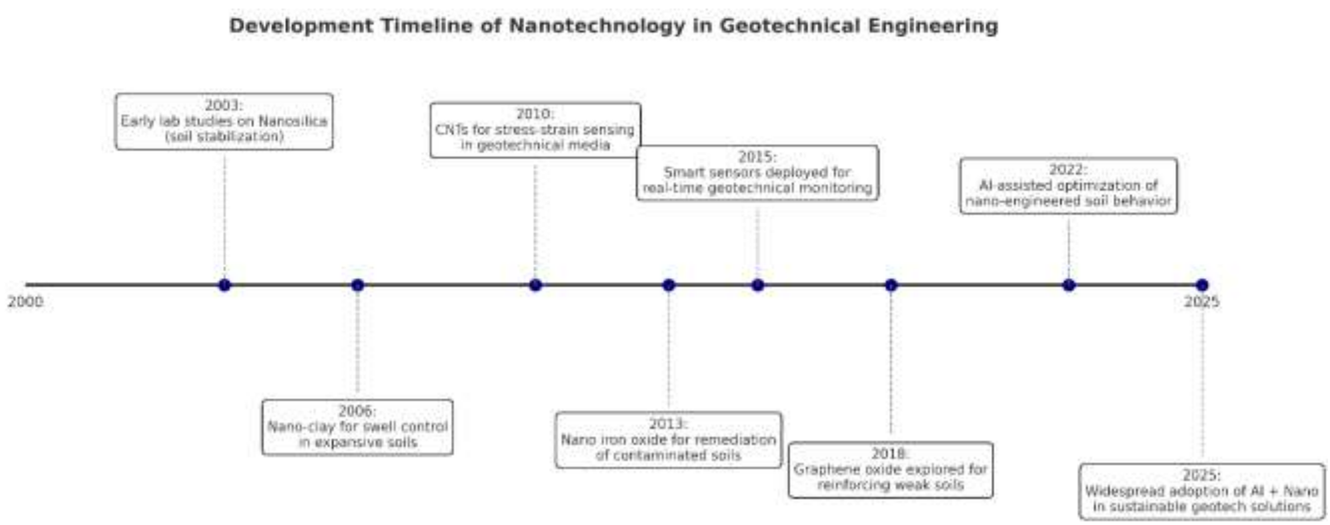

Figure 3: Shows the Development Timeline of Nanotechnology in Geotechnical Engineering (2003–2025)

2.1 Nano Material

Table 1 presents a comparative assessment of four widely 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 is 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.

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

Key Insights:

- Nano-silica demonstrates excellent performance in dry and loose sands (score: 9) due to its strong pozzolanic activity, which densifies granular soils. It also performs well in expansive soils (score: 8), but is 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 sands.
- 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 concerns.
- 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.

2.1.1. Nano-silica

Nano-silica (SiO_2) is recognized as a significant nanomaterial in geotechnical engineering, attributed to its distinctive physicochemical properties, such as a fine particle size (generally between 10–80 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, or fly ash(Changizi and Haddad, 2023, Bayat, 2025, Chaudhary et al., 2024, Harsh et al., 2023). Nano-silica enhances soil performance primarily by reacting with calcium hydroxide ($Ca(OH)_2$), 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 rise in 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 including 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, which can lead to inconsistent performance. Researchers have investigated the combined application of nano-silica with various additives, including nano-alumina, polypropylene fibers, and enzymes, to improve mechanical and hydraulic properties(Bayat, 2025, Asad et al., 2024, Dheyaaldin et al., 2022b, Dheyaaldin et al., 2022a).

2.1.2. 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).

Nano-clays demonstrate significant adsorption capabilities in environmental applications, 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 the remediation of contaminated soils and groundwater. Engineered modified nano-clays, such as organo-nano-clays, have been designed to specifically target pollutants, thereby improving their application in geotechnical and environmental engineering. Modified clays are applicable in permeable reactive barriers (PRBs) and soil washing systems for site remediation and groundwater treatment.

2.1.3. 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 present. Carbon nanotubes (CNTs) exhibit exceptional mechanical, electrical, and thermal properties, including high tensile strength (100 times that of steel), lightweight characteristics, 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 utilized 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 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 assessment. 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).

2.1. 4. 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 formation. 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's resistance to water infiltration, shrinkage, and freeze-thaw degradation. In addition to their mechanical advantages, graphene and graphene oxide are particularly well-suited for the development of smart, sensor-integrated soil systems owing to their superior electrical conductivity.

The adsorptive capacity of GO renders it an effective material for environmental remediation. GO sheets possess the capability to 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, attributed to their numerous functional groups and strong affinity for these pollutants. Graphene oxide is a promising candidate for in-situ treatment of contaminated soils, landfills, and groundwater barriers. The performance in 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 within 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 are contributing 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, or the application of dispersing agents is frequently utilized to address this issue.

2.2 Smart Material

Smart materials exhibit responsiveness to environmental stimuli, including stress, temperature, and damage, rendering them particularly significant in dynamic soil-structure interactions. Piezoelectric sensors are utilized in foundations, slopes, and embankments for the purpose of real-time monitoring of stress and strain. The capacity to produce electrical signals in reaction to mechanical stress facilitates ongoing evaluation of structural integrity. Shape Memory Alloys (SMAs) possess the capability to revert to a predetermined configuration upon exposure to designated temperature thresholds. Shape memory alloys (SMAs) are utilized 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 via embedded healing agents. This enhances long-term durability and minimizes maintenance requirements.

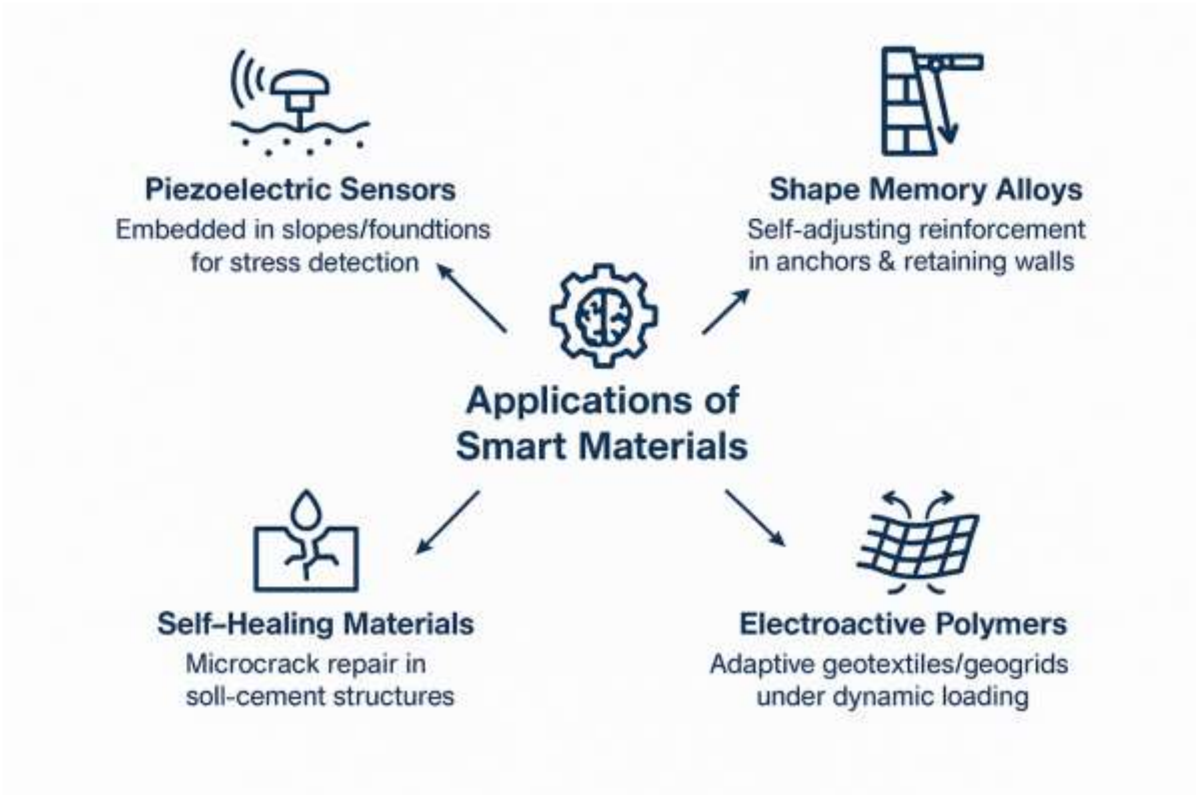

Figure 4 Illustrates the diverse and emerging roles of smart materials in geotechnical engineering.

2.2.1. Piezoelectric materials

Piezoelectric materials represent a category of 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, especially within 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 utilized piezoelectric material in geotechnical applications, recognized for 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:

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 are capable of detecting micro-deformations and transmitting early warning signals prior to the occurrence of macroscopic failure. This proactive capability can substantially mitigate risk and facilitate timely maintenance.

2. Seismic and Vibration Sensing: Piezoelectric elements embedded in soil layers exhibit rapid responses to dynamic loading, functioning as seismographs or vibration detectors. They are capable of capturing data during construction activities, traffic-induced vibrations, or natural earthquakes.

3. Energy Harvesting Systems: Piezoelectric materials possess significant potential for energy harvesting. In areas with high traffic, mechanical vibrations generated by vehicles can be harnessed to produce electricity through piezoelectric soil beds, supplying energy for 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 soil behaviour. 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 in 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.

2.2.2 Shape Memory Alloys

Shape Memory Alloys (SMAs) represent 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. The predominant shape memory alloys are nickel-titanium alloys (NiTi or Nitinol) due to its 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 geosynthetics. Shape memory alloy (SMA) rods or tendons used in deep foundations or ground anchors may deform under seismic strain and then revert to their original shape when heated by friction or an externally provided current that produces 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 needs. 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 and Ranjan, 2025, Tabrizikahou et al., 2022, Abedi et al., 2023).

2.2.3. Electroactive Polymers (EAPs)

Electroactive Polymers (EAPs) represent 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 functionality 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 real-time monitoring of deformation, pore pressure variations, or soil settlement. EAPs can also be used to increase electro-osmotic flow for pollution removal or soil dewatering.

Electroactive polymers (EAPs) can convert mechanical strain from wind, seismic activity, or car vibrations into useable electrical energy for energy harvesting applications. This capability makes it easier to create self-sufficient geotechnical monitoring systems, particularly in isolated or off-grid areas. In order to power wireless communication modules, convey sensor data, or activate other smart material components inside the system, the collected energy can be stored. The soft and elastic characteristics of EAPs enhance their compatibility with soil matrices in comparison to conventional rigid sensors or actuators.

2.2.4. Self-Healing Materials in Geoengineered Soils

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

There are several mechanisms by which self-healing can be induced in soil-based materials:

Encapsulated healing agents represent a prevalent method that incorporates microcapsules or hollow fibers containing healing substances, including epoxy, polyurethane, or silica-based gels, within soil-cement composites. Upon the formation of a crack, the capsules rupture, thereby 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 the crack. This method has demonstrated efficacy in restoring strength and impermeability in stabilized soils and cementitious ground improvement systems.(Qi et al., 2024, Souradeep and Kua, 2016, Harbottle et al., 2014, Al-Tabbaa and 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 reaction to environmental changes. These microorganisms are either integrated directly 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. MICP presents 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 the formation of cracks, these intelligent capsules undergo deformation to release the healing agent or actively expand to seal the gap(Qi et al., 2024, Souradeep and Kua, 2016). This method facilitates precise healing with enhanced control and efficiency, particularly beneficial in dynamic soil conditions or regions subjected to frequent loading and unloading cycles.

Self-healing materials in geoengineered soils offer numerous advantages. They enhance the longevity and resilience of geostructures by effectively mitigating crack growth and damage progression(Chang et al., 2024, Zhang et al., 2024). Furthermore, they enhance sustainability by minimizing the necessity 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. Nano-scale additives can improve self-healing efficiency from a nanotechnological perspective. Nano-silica or nano-clay particles serve as nucleation sites for healing reactions and enhance the dispersion and efficacy of encapsulated healing agents.

3. Current Applications of nano material and smart material in Geotechnical Engineering

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

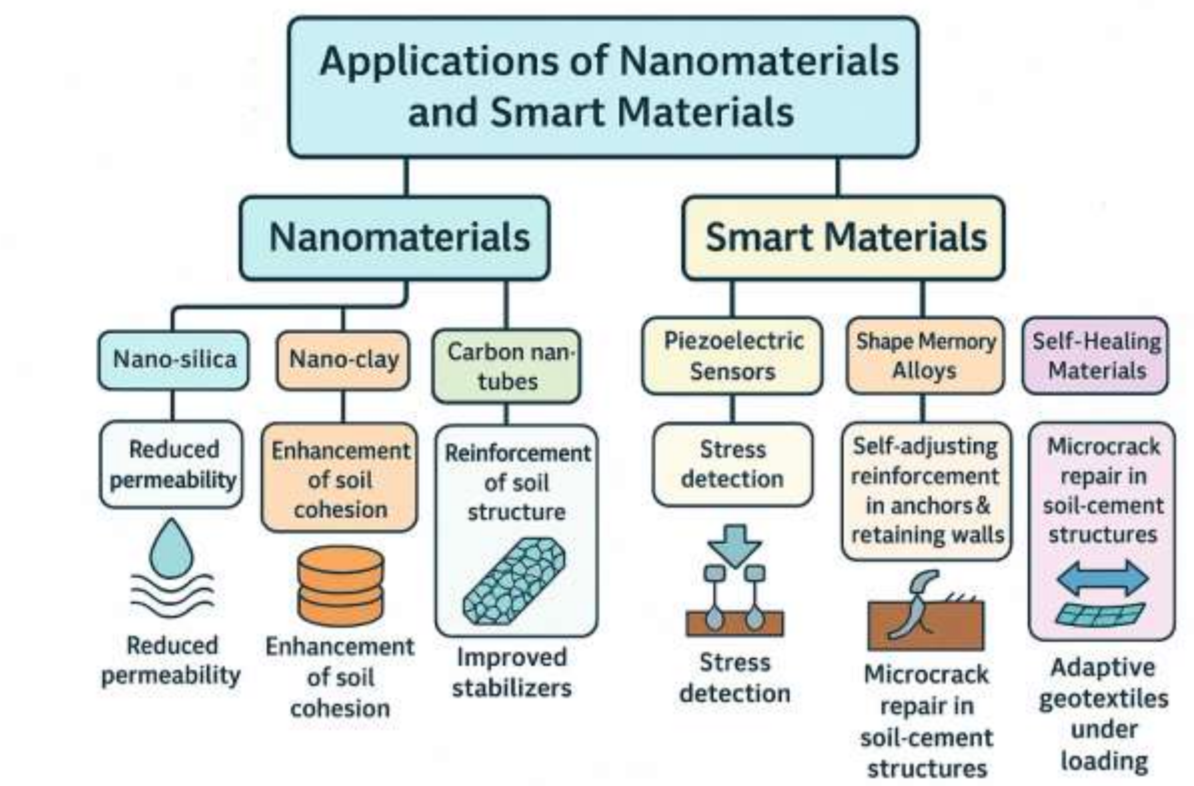

Figure 5 Shows the applications of Nano material and Smart Materials in Geotechnical Engineering.

3.1 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 conventional approaches(Zhang et al., 2020, Majeed and Taha, 2013, Biswal and 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 utilized for the stabilization of expansive and loose soils. When combined with cement or lime, nano-silica improves pozzolanic reactions and occupies micro-pores in the soil matrix, leading to a denser, more cohesive structure characterized by enhanced unconfined compressive strength and decreased permeability. Nano-clay 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 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). The materials, recognized for their exceptional tensile strength and electrical conductivity, are under investigation for the development of multi-functional 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 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, attributed to their responsive behaviour to environmental stimuli. Piezoelectric materials are embedded in geotextiles and foundation systems to monitor ground vibrations, soil movement, and stress fluctuations in real time.

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

The integration of nanotechnology and smart materials has markedly progressed geotechnical sensing and monitoring, allowing engineers to transition from reactive to proactive infrastructure management. Nanomaterials and smart materials are increasingly integrated into infrastructures and subsurface environments to provide real-time, precise, and intelligent monitoring solutions(Husen and Siddiqi, 2023, Das et al., 2015, Sharma et al., 2021). These innovations hold significant importance 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.

3.3 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 and Wang, 2016). Traditional ground improvement methods, including compaction, grouting, soil replacement, and chemical stabilization, are being enhanced through the integration of advanced nanomaterials such as nano-silica, nano-clay, nano-calcium carbonate, and carbon-based nanostructures. The materials enhance 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 especially effective for the treatment of soft clays, loose sands, and expansive soils frequently encountered in infrastructure development.

4. Environmental Linkages and Sustainability Aspects

Advancing responsible innovation necessitates 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, identifying opportunities to enhance resource efficiency and reduce emissions. Despite the technical advantages, concerns persist over 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 or 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 the future of 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 production, carbon footprint, eco-toxicity, and long-term durability. These factors assess both the functionality of nanomaterials and their sustainability and ecological impact throughout their life cycle.

Figure 6 indicates that nano-clay possesses a balanced environmental profile characterized by high biodegradability, low eco-toxicity, and minimal energy consumption, rendering it suitable for sustainable soil enhancement. Nano-silica demonstrates high durability but exhibits lower biodegradability and necessitates moderate energy consumption. Carbon nanotubes (CNTs) exhibit significant durability; however, they present issues related to high production energy, 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. Figure 6 facilitates the selection of nanomaterials by incorporating both technical efficiency and eco-conscious engineering considerations in contemporary geotechnical practice.

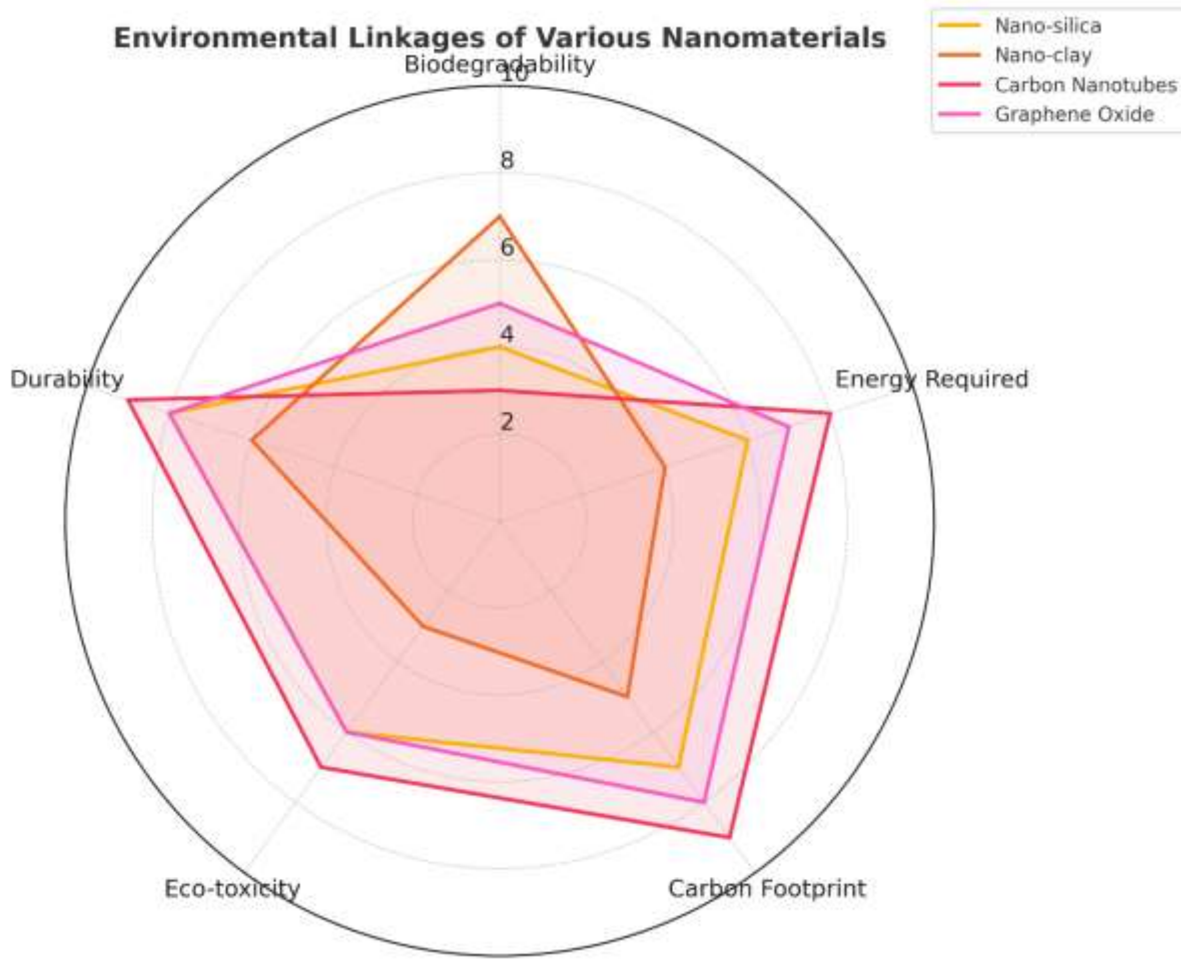

Figure 6 Shows the environmental linkage of various Nanomaterials

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 (Figure 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.

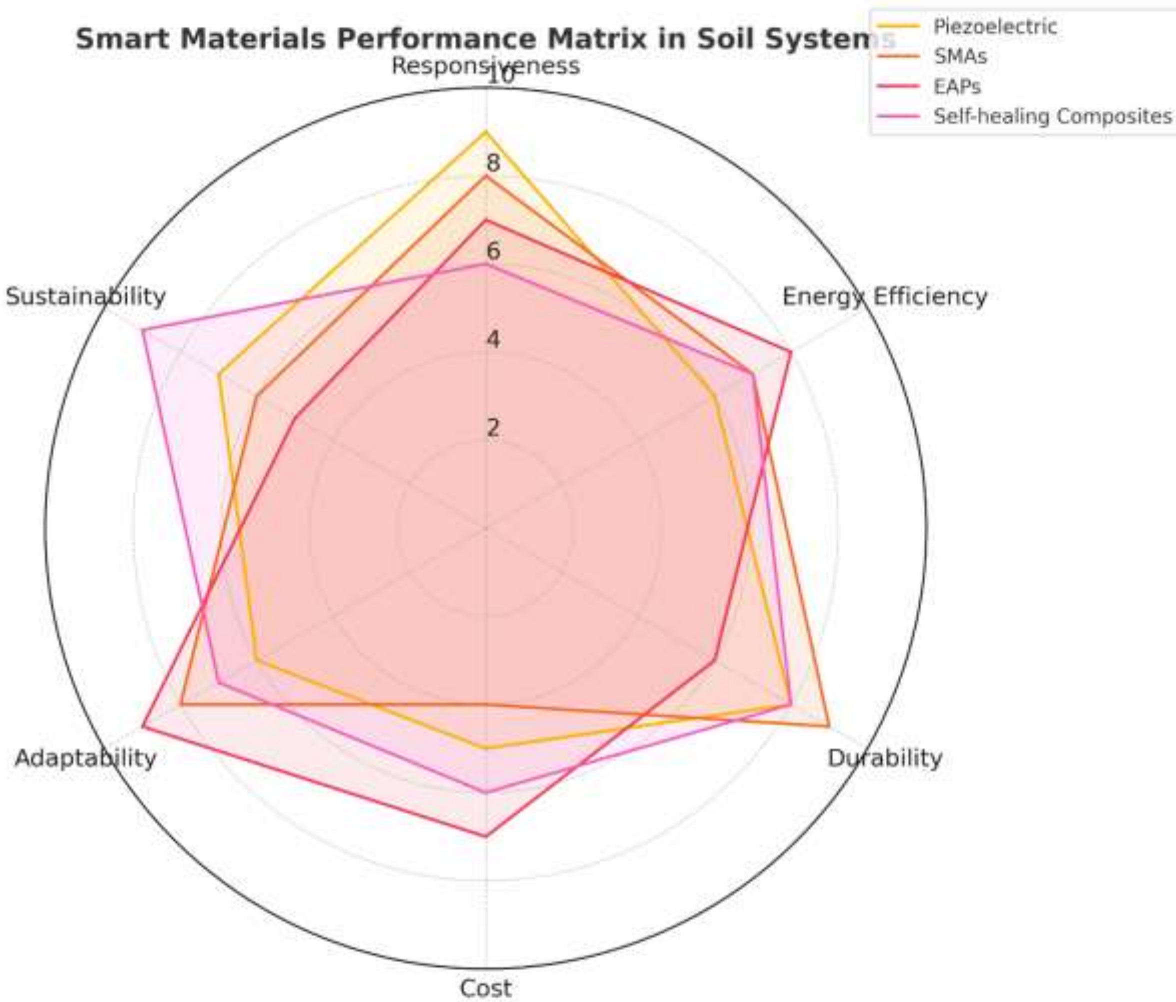

Figure 7 Shows the Smart Materials Performance Matrix in Soil Systems

4.1. Life Cycle Assessment (LCA) of Nanomaterials and smart materials in Soil Engineering

The use of nanomaterials and smart materials in soil engineering methods improves performance, monitoring capabilities, and the 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 stabilisation(Hischier and Walser, 2012, Visentin et al., 2021, Gallagher et al., 2017).

The use of nanomaterials and smart materials in soil engineering methods improves performance, monitoring capabilities, and the 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 stabilisation [117-119].

Nanosilica (Precipitated): LCA case study (China): Renewable electricity (wind, hydro, solar) reduces emissions by 40–90% compared to 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 toxicity impact.(Arvidsson, 2017)

2. 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)

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

4.2 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 comprehended aspects of the LCA framework. Enhanced soil strength, real-time sensing, and adaptive behavior are among the performance benefits these materials provide; nevertheless, 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. The materials may adversely affect plant roots, soil microbes, and groundwater chemistry due to their diminutive size and elevated surface reactivity. Research indicates that specific nanoparticles can modify soil fertility by influencing 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).

A serious risk is bioaccumulation, particularly when nanoparticles are left in the environment without being sufficiently broken down. These materials can be assimilated by soil creatures 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).

Figure 8 depicts the environmental risks associated with the use of smart and nano-engineered materials in geotechnical applications. The materials' long-term environmental behavior is a major concern, despite their tremendous advantages in 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.

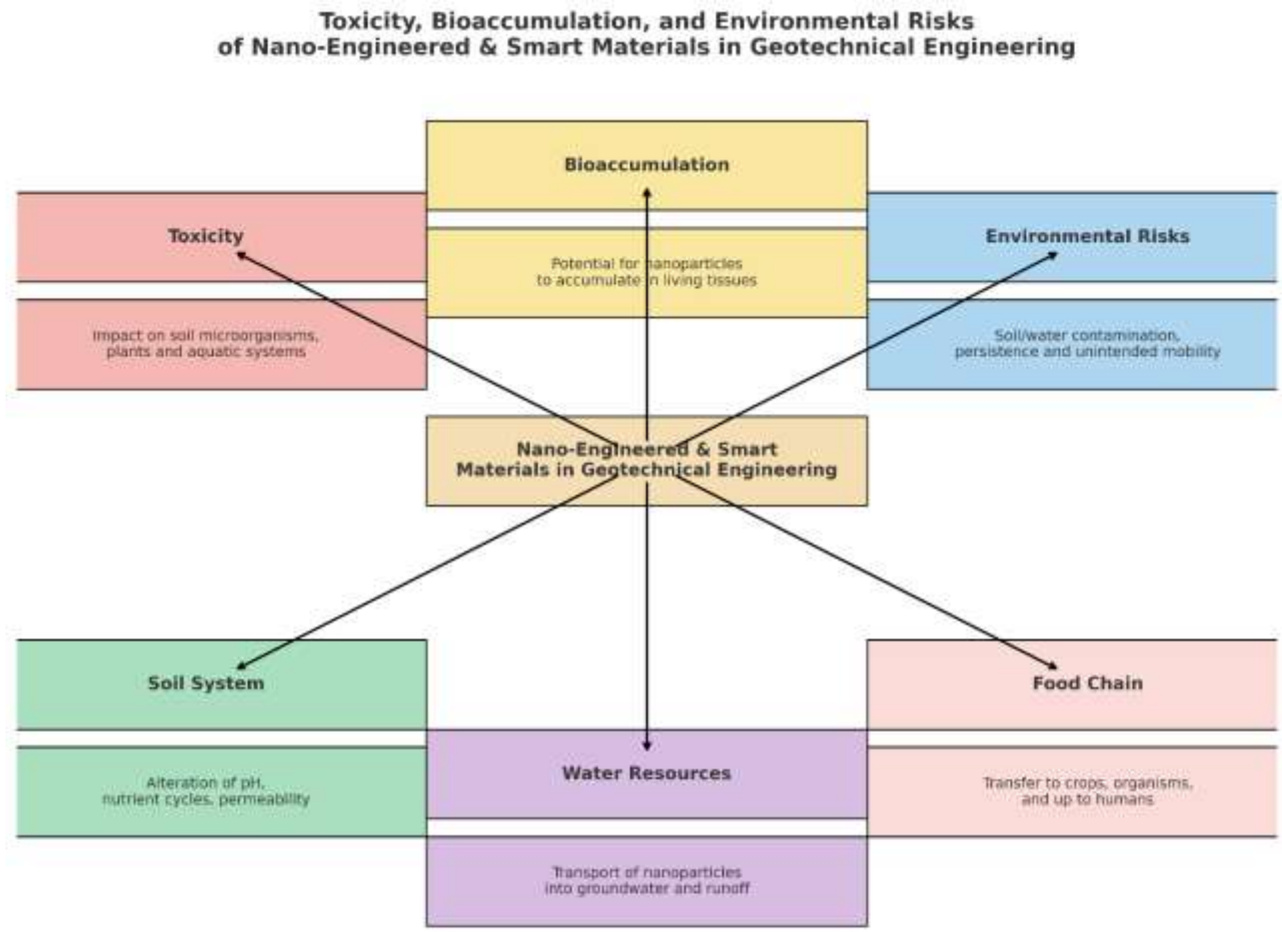

Figure 8. Shows the Toxicity, Bioaccumulation, and Environmental risks associated with nanomaterial and smart material.

3.3 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 characterized by extraction, utilization, and disposal. The emergence of nano 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 feedstock for nanomaterials represents a promising approach. Nano-silica can be synthesized from rice husk ash or waste glass, both of which are readily available and underutilized resources. This approach reduces the demand for virgin materials and diverts agricultural or industrial waste from landfills, thereby supporting a circular economy. Figure 9 illustrates the circular economy of nanomaterials within the geotechnical field.

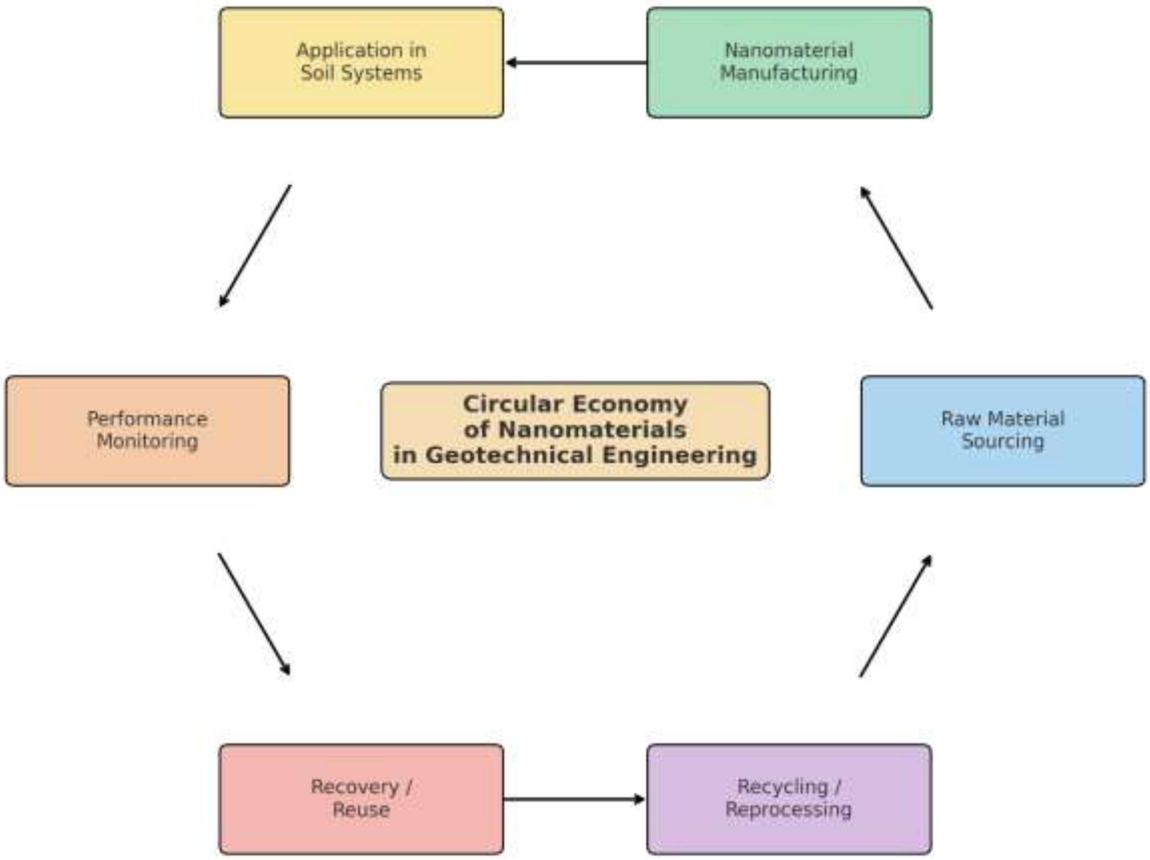

Figure 9 Shows the circular economy of nanomaterial in geotechnical field.

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

3.4 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 mainstream adoption. This section outlines the current state of available standards

(ASTM, ISO, IS, OECD, USEPA, and REACH) and highlights gaps where nanomaterial-specific guidance is either lacking or under development.

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

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

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

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

4. **Challenges and Limitations**

Although advancements in nanomaterials and smart materials for geotechnical engineering are promising, various challenges and limitations impede their widespread adoption. The primary technical challenge is the difficulty in achieving uniform dispersion of nanoparticles within soil matrices, which impacts their efficiency and performance. The scalability of lab-based innovations to large-scale geotechnical applications presents a significant challenge, 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. The cost is a significant barrier since, especially in situations with limited resources, 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 and Velidandi, 2025).

4.1 Dispersion, scalability, and long-term behaviour:

Despite the significant potential of using 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 behaviour in complex soil environments are critical issues. A significant difficulty confronting soil matrices is the proper dispersion of nanoparticles. Robust van der Waals forces induce a tendency for nanomaterials such as graphene oxide, carbon nanotubes (CNTs), and nano-silica to aggregate. This aggregation reduces their functional capabilities and surface area. Achieving homogeneous mixing at the nano-scale 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.

4.2 Lack of standards, guidelines, and regulatory frameworks

Notwithstanding 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 like nano-silica, carbon nanotubes, and graphene in soils is marked by an 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 design 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.

4.3 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 in relation to their production, processing, and large-scale use. Laboratory investigations and pilot-scale applications have shown that nanomaterials have a number of advantages, including as enhanced strength, reduced permeability, and self-sensing capabilities. However, their synthesis and modification are still sometimes prohibitively costly. Complex manufacturing processes that necessitate controlled conditions, specialized equipment, and significant energy investment are needed to produce materials like carbon nanotubes, graphene oxide, and high-purity nano-silica. Due to their higher production costs, these features render their use in large-scale infrastructure projects economically impractical, as cost-effectiveness is a key concern.

5 Future Potential and Research Directions

Nano-engineered and smart materials have significant potential applications in geotechnical engineering, particularly when combined with advanced technology and environmentally friendly advancements. 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 nano sensors 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 validations 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 for the future.

5.1 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 due to the growing complexity of infrastructure demands brought on by urbanization, climate change, and sustainability goals. When integrated in the soil matrix, smart materials such as piezoelectric sensors, shape memory alloys, and electroactive polymers serve as sensory nodes that pick up on variables like strain, pressure, moisture content, and temperature changes. By using IoT-enabled devices to network these materials, engineers may establish interconnected geotechnical settings that provide constant streams of data for in-the-moment decision-making.

5.2 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 in developing environmentally responsible and resource-efficient ground improvement methods. In contrast to traditional nanomaterials that typically require energy-intensive production methods and pose ecological risks, bio-inspired nanomaterials are sourced from natural systems, processes, or organisms, emulating nature's mechanisms of stabilization and self-healing. These materials are generally biodegradable, non-toxic, and renewable, which aligns with circular economy principles and reduces long-term environmental impacts. A notable example in this field is microbially induced calcite precipitation (MICP), wherein 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 a fine particle distribution, facilitating more effective bonding.

5.3 Field-scale validations and performance monitoring

Laboratory investigations have shown the potential of nano-engineered and smart materials to improve soil behavior; however, the transition from laboratory-scale studies to real-world field applications is 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 across various environmental and loading conditions. Future research should focus on large-scale trials to evaluate the performance of nano-silica, nano-clays, 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 performance enhancements, including increased shear strength, reduced settlement, and improved drainage. Additionally, they will offer insights into material behaviour over extended periods, encompassing aging, degradation, and interactions with soil chemistry.

Conclusions

Significant opportunities in geotechnical engineering have been created by the quick development of nanotechnology and the appearance of smart materials. In order 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 gains in mechanical and physical characteristics, such as shear strength, stiffness, water retention, and reduced permeability, have been demonstrated by the incorporation of nanomaterials into soil systems, including graphene, carbon nanotubes (CNTs), nano-silica, nano-clay, and nano-calcium carbonate. Because of these advancements, soil treatments based on nanomaterials can now effectively replace traditional soil stabilization methods, especially for challenging soils. Geotechnical systems are now dynamic, adaptive entities instead of static ones because too smart materials such as piezoelectric materials, shape memory alloys (SMAs), electroactive polymers, and self-healing composites. These materials have the ability to perceive environmental stimuli like strain, temperature, or stress and respond instantly through self-healing or actuation mechanisms. By integrating monitoring and adaptive reaction 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 developing environmentally friendly engineering methods. Life Cycle Assessment (LCA) studies have started to clarify how these advanced materials affect the environment, pointing out potential benefits as well as risks. Adsorbing heavy metals or other contaminants from contaminated soils is one way that some nanomaterials, like nano-alumina and nano-iron oxides, improve environmental remediation. However, some have legitimate concerns about toxicity, bioaccumulation, and potential environmental disruption. One important area for future research is the development of ecologically friendly synthesis techniques and sustainable, biomimetic substitutes. Particularly as infrastructure systems work toward sustainability and climate resilience, the role of these materials in a circular economy—which is characterized by waste reduction and the recycling or repurposing of resources—is an important area of focus.

Notwithstanding these benefits, a number of important issues need to be resolved before widespread implementation is thought to be possible. Significant technical obstacles still exist, including the consistent dispersion of nanoparticles in various soil types, long-term stability and behaviour, and the scaling from lab settings to field applications. The economic feasibility of utilizing high-cost nanomaterials in resource-constrained geotechnical projects restricts their broad implementation. Gaps in regulatory oversight and standardization are significant; there is currently an absence of universally accepted protocols, performance benchmarks, and safety guidelines for the use of nanomaterials and smart materials in soils. Overcoming these challenges requires multidisciplinary research collaborations, transparent policy formulation, and efforts toward global standardization. The future of geotechnical engineering is positioned at the convergence 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, self-regulating geotechnical systems. Smart soil systems have the capability to monitor subsurface conditions, predict failures, and respond adaptively, thereby enhancing the intelligence and resilience of infrastructure. The investigation of bio-compatible, 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 must be prioritized to validate and scale these innovations. The integration of nano-engineered soils with smart materials presents significant opportunities to transform geotechnical engineering, 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 sustainable infrastructure development.

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