Intelligent Nanotechnology Applications in Subgrade Stabilization and Pavement Engineering

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Abstract: Nanotechnology has emerged as a transformative approach for enhancing the performance of subgrade soils and pavement materials through nanoscale modification in their physicochemical and mechanical behavior. This technical note represents various aspects of the nanomaterials in subgrade stabilization and pavement engineering, covering flexible and rigid pavements. Nanoparticles improve soil performance through hydration and pozzolanic reactions which subsequent result in void filling and surface modification to produce a dense soil matrix. In flexible pavements, nanomaterials enhance rutting resistance, fatigue life, moisture stability, and optical properties of asphalt binders. In rigid pavements, nanosilica and related additives refine microstructure, strengthen the interfacial transition zone, and significantly improve strength and durability of concrete. The note further highlights environmental benefits, cost efficiency, durability enhancement, and emerging role of intelligent modeling and data-driven methods for optimizing nanomaterial performance. Overall, nanotechnology offers a sustainable, high-performance, and future-ready solution for subgrade stabilization and pavement engineering applications.

Keywords: Nanotechnology, Soil stabilization, Pavement engineering, Nanosilica, Intelligent geotechnics.

INTRODUCTION

The term ‘Nanotechnology’ was first coined by American physicist Richard Feynman during a speech delivered in the year 1959. This new age technology introduced the nanoscale structures to the world (Kaehler, 1994; Drexler, 1981). This modern technique deals with the particles of size <100nm as shown in Figure **1** (Cardinaud *et al*., 2000; Sobolev and Gutiérrez, 2005). Finest nanomaterials impart the unique characteristics, those collectively produce four related effects *i.e*., size, quantum, surface charge and, interfacing in the product. Now-a-days, nanomaterials have wide applications in the field of engineering, agriculture, medical, forensic, energy, health, biotechnology, information, and so on (Dey *et al*., 2018; Devi and Kumar, 2022; Kumar and Devi, 2022; Kumar and Devi, 2023). Nanomaterials can be produced through two approaches namely, Top Down and Bottom Up; where, in former case, bigger particles (macroscopic articles) get break down to the nano size and in later case, atomic or molecular substances grouped into nanomaterials (Sobolev and Gutiérrez, 2005). Both phenomena have been shown in Figure **2**.

Superior performances and reliable outputs are the prime reasons for using the nanomaterials in pavement construction material and subgrade improvement. The nanomaterials have capability to modify the inherent properties of construction materials. Seasonal freeze-thaw and rainfall introduce the continuous disintegration and strength degradation to subgrade soils (Zhang *et al*., 2019; Zhang *et al*., 2020). Cyclic weathering actions reduced the shear strength of soils. Use of nanomaterials provides durability and enough strength to bear or maintain stability in the soils (Rao *et al*., 2015). During mixing of nanomaterials in the soil, two aspects are considered (a) improvement in soil properties (b) revealing the mechanism of improvement (Zahedi *et al*., 2014; Ganesh, 2012). In pavement engineering, nanomaterials can be used for both flexible as well as rigid pavement. In case of flexible pavements, nanomaterials are employed to resist the rutting and fatigue effects. In rigid pavements, pozzolanic nanomaterials *e.g*., nanosilica infuse the dense microstructure and help to produce more impermeable matrix (Yusak *et al*., 2006; Yang and Tighe, 2013) with better mechanical and durability properties (Balapour *et al*., 2018). After years of research, there is still lack of valuable and prolific work regarding the application of nanomaterials in subgrade and pavement engineering.

Presented technical note deals with the overview of the well-known studies in the use of nanomaterials in subgrade and pavement engineering, discussing physical, mechanical, durability, and microstructural analysis of various subgrade soils for both, flexible and rigid pavements. Moreover, environmental studies and cost analysis of the nanomaterials have also been discussed. Finally, the benefits of nanomaterials over traditional materials have been summarized in the note. In addition, the emerging role of intelligent modeling, numerical simulation, and data-driven approaches in predicting the performance of nanomaterial-treated soils and pavements has been highlighted. The integration of artificial intelligence and machine learning tools for performance optimization, dosage prediction, and durability assessment is also discussed to support next-generation smart infrastructure

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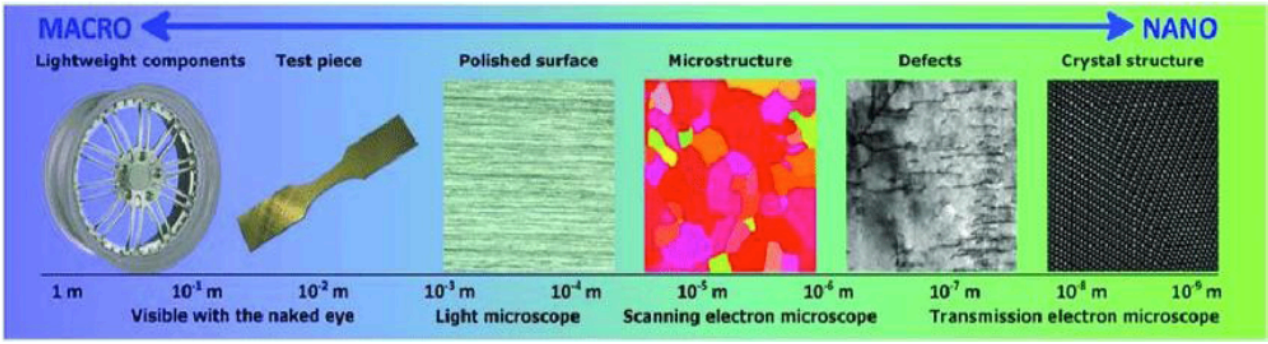

Figure 1: Evaluation of particles from macro to nano scale.

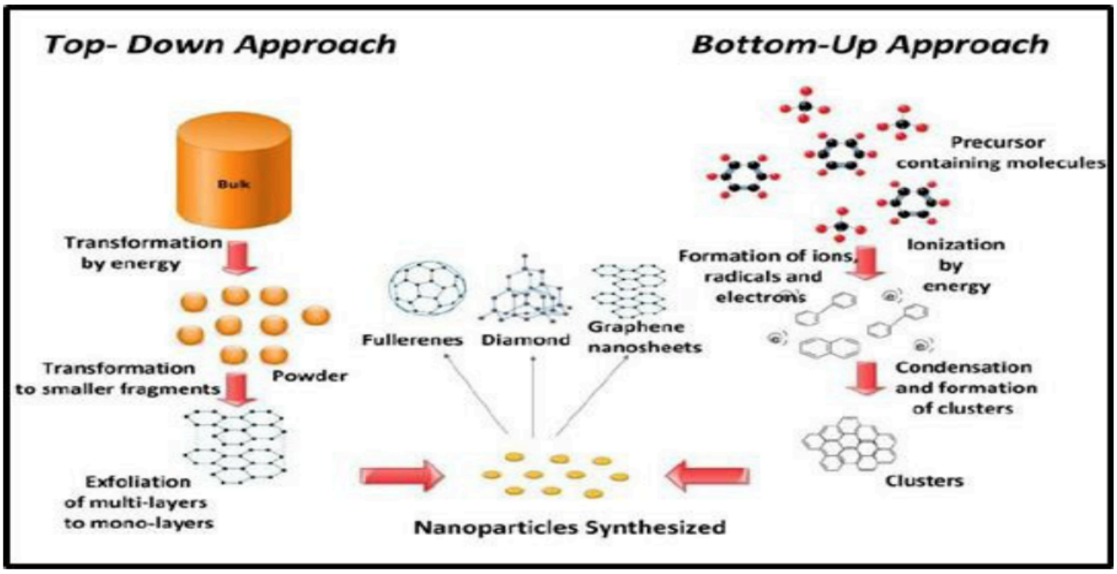

Figure 2: Formation approaches in nanotechnology.

development. These advancements collectively position nanotechnology as a key enabler for sustainable, resilient, and intelligent geotechnical and pavement systems.

APPLICATIONS OF NANOMATERIALS IN SUBGRADE SOILS

Though traditionally cement or lime-based stabilizers are being used in stabilizing the fine-grained soils. Recent advances in technologies are seeking other favorable options *e.g.*, nanomaterials, in subgrade improvement for better durability and lesser erosion. Therefore, it is pre-requisite to know about the mechanisms by which nanomaterials act and modify the various engineering and microscopic properties of the soils.

Physiochemical Properties

Various researchers have explored the mechanisms behind the physical and chemical changes in different soils. A study on multi-walled carbon nanotubes and nanofibers utilizing in subgrade soil demonstrated the void filling and bonding effects those increased the dry density and decreased the hydraulic conductivity (Taha and Jamal, 2018). In a study, nanomaterial resembling to volcanic ash promoted the ion exchange and hydration reaction among soil particles. These reactions increase the flocculation and stiffness in expansive subgrade soil (Chibuzor and Duc, 2018). Scholars have proved that incompatible nanomaterials like nanoclay, nanoalumina and nanocopper do not react with soil grains but their fine particles fill the soil pores perfectly and, therefore, helped to increase the density and decrease the desiccation behavior of the soils (Taha and Taha, 2012). Similar results have also been reported in another report. But, contrarily soil reactivity was found high and microstructural studies showed calcium silicate hydrate (CSH) and calcium silicoaluminate hydrate (CASH) gel formation in the soil voids (Lv *et al*., 2018). Among all, nanosilica is highly reactive and have significant effects on the soil properties (Lin *et al*., 2016). Nanomagnesia, an expansion agent, also promoted the hydration reactions and produced uniform and strong microstructure to fill the capillary pores in the cement paste (Polat *et al*., 2017).

In concluding remarks, it can be reported that mixing of nanomaterials into different subgrade soils initiate the chemical reactions those change the physical properties of the treated soils positively. Nanomaterials' filling effects improve soil denseness and compactness, indirectly enhancing shear resistance by producing cementitious products within the matrix. Therefore, reactivity of nanomaterials, factors affecting, and time lapse for reactions etc. could be key issues for prospective researchers.

Strength Properties

Past studies have proved that the use of nanomaterials improved the strength and mechanical properties of various soils up to the extent to meet the requirements of subgrade and pavements. Nanocomposite polymer (15%) in expansive clay decreased the expansion ratio by 90% and, increased the soil stiffness and unconfined compressive strength by 4.5 times and 2.2 times respectively, after fully oxidation, completed in 4 weeks (Azzam, 2014). In the row, glass fibers and nanoparticles in duo have increased the strength of clay with respect to single fibrillated glass fiber. The proportions of fibers, varied from 0.5% to 1.5%, in Nanoclay increased the shear strength by 84% (Meng *et al*., 2017). Nanocopper (1.5%), introduced in black cotton soil, improved the compressive strength by more than 300% and decreased the expansion pressure about 22% (Pusadkar *et al*., 2017). Terrasil, a type of nanomaterial, also proved good in improving the geotechnical properties and shear resistance of local soil. California Bearing Ratio penetration was also improved, which is essential for a pavement to be laid (Ewa *et al*., 2016). Nanomagnesia, optimal as 15%, gave satisfactory strength with 13% cement content (Yao *et al*., 2019). Nanosolution and flyash (30%), in mixture, improved the CBR and decreased the co-efficient of permeability in expansive silty soil subgrade. Above 85% decrease in permeability co-efficient was also reported (Kulkarni and Mandal, 2017).

Though, various nanomaterials have improved the soil strength but, their effectiveness ultimately depends upon soil type, additives to be mixed; in nature and quantity, and targeted mechanical properties of the soil. Therefore, still thorough and extensive studies are required to get into the depth of the strength gain phenomenon.

Morphological Mechanism Analysis

Nanomaterials primarily improve subgrade soil properties by reducing micro porosity through pore-filling effects. The filled micropores cannot be observed through naked eyes, so, sophisticated microscopic instruments are used for the purpose. These instruments are so much capable in detecting the changes before and after adding the additives into the soils. These state-of-the-art techniques have been proven so much accurate that today every scholar and potential researcher must have a keen knowledge of them.

Weak kaolin, when treated with nanosilica and silica fume, found improved and the changes have been detected by microscopic techniques. The micrographs proved the filling effect, responsible for potential strength gain (Ghavami *et al*., 2018). The pozzolanic reactions of nanomaterials and binding effect of coir fibers were detected through scanning electron microscopy (Anggraini *et al*., 2016). Another study revealed that the nano-composites, in the presence of water, produce cementitious products those filled the voids and get wrapped around the soil particles. The filling and wrapping effects increase the effective contact areas between soil particles and improve the ultimate interfacial bond strength and friction (Meng *et al*., 2017). Moreover, nanosilica also have the same effect on silty soil and show better shear performance (Cui *et al*., 2018). Cement-nanosilica-modified clay also exhibits improved strength properties due to enhanced pozzolanic reactions and the resulting pore-filling effects (Ghasabkolaei *et al*., 2016). A typical filling mechanism demonstration has been shown in Figure **3**.

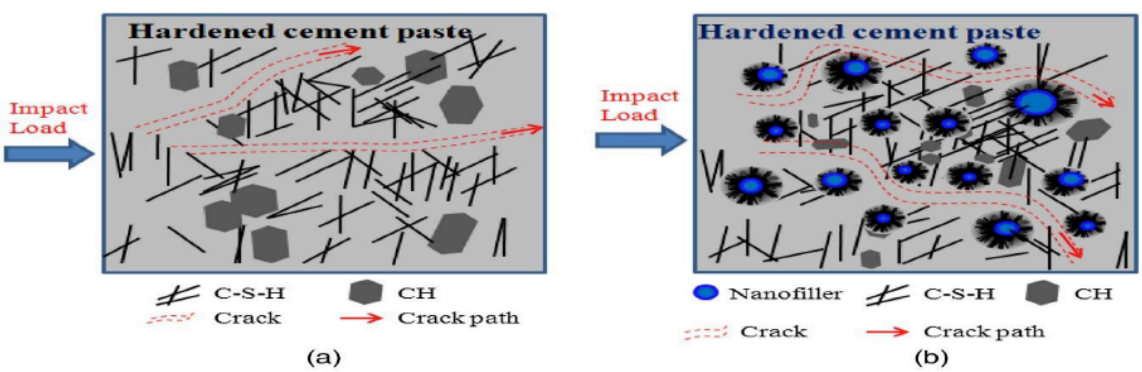

Figure 3: Filling effect in concrete.

It has been noted that nanoalumina not only creates filling effect but also produces complex gelatinous products after reacting with soil particles and improves the mechanical behavior of soil (Zeng *et al*., 2017; Guo *et al*., 2019). Complexity of pozzolanic reactions produced gelatinous products, still make the microstructural analysis, a case of study. There is a genuine need of research in the field of microstructural analysis of nanomaterial improved soils.

Based on SEM and microstructural interpretations the figure explicitly represents nano-scale pore filling, particle wrapping, and formation of cementitious reaction products (CSH and CASH gels) within soil voids. These mechanisms are directly associated with documented reductions in microporosity, increased effective contact area between soil particles, and enhanced interparticle bonding. These microstructural changes increase the shear strength, stiffness, and unconfined compressive strength, as well as reduce permeability and compressibility parameters that govern bearing capacity improvement, settlement mitigation, and subgrade stability under pavement and foundation loading.

Although, nanomaterials have been proved as excellent soil stabilizers but still there are so many things to put together in this regard. Nanomaterials improve the soil behavior by physicochemical reactions but, agglomeration and flocculation of additives are still the bottlenecks for researchers because these cannot be avoided but minimize. For long-term soil stability, durability studies on nanomaterial-treated soils remain unexplored.

NANOTECHNOLOGIES IN PAVEMENT ENGINEE-RING

Nanotechnology not only has its wide applications in improving the subgrade soils but also in constructing more long-lasting and durable pavements. The unique inherent properties of nanomaterials find them suitable for improving and correcting the various pavement properties *e.g*., water stability, rutting and fatigue etc. Following sections contain the details about the application of nanomaterials in flexible as well as rigid pavements.

Flexible Pavement

Nanotechnology has been utilized in flexible pavements to improve the significant properties of asphalt binder. Nanomaterial modified asphalt showed better uniformity and water stability with high rutting and fatigue resistance. Nanorubber was also found a suitable modifier for the fatigue resistance at low temperature (Saltan *et al*., 2017; Saltan *et al*., 2018; Chen and Zhang, 2012). The ageing process in asphalt is actually commenced after the chemical reactions in functional groups. The reactions contain old and newly formed carbonyl group. Nanozycosoil and nanosoil are the potential nanomaterials for the commencement of functional group-based reactions (Golestani *et al*., 2012; Yao *et al*., 2015 a,b). The nanomaterials have also improved the water sensitivity in the asphalt mixtures (You *et al*., 2011; Behbahani *et al*., 2015; Ziari *et al*., 2015). Some optical properties, such as enhanced solar energy absorption and reduction in pavement surface temperature, have also been observed (Wang *et al*., 2013). The acrylic composites have highest solar reflection and thereby reduce the pavement temperature during day time. A study on vehicle emission mitigation showed that nano-TiO_2 photocatalysts effectively removed NO_x from traffic emissions, achieving a decontamination efficiency of approximately 6-12% (Chen and Liu, 2010).

Rigid Pavement

Alike flexible pavements, the performance of nanomaterials in rigid pavements totally dependent upon size of additives. Therefore, nanomaterials in concrete pavements also have potential for the strength gain and repair of shortcomings. Since it is gaining popularity so, many countries have formulated the guidelines for the proper usage of these revolutionary materials (Birgisson *et al*., 2010). Most of the nanoscale additives are best suited with cement. Their performances after mixing with the cement are extraordinary. Nanosilica is one of them (Heikal *et al*., 2013; Ibrahim *et al*., 2015). Nanosilica acts in two ways: it enhances the interfacial bonding between the paste and aggregates, thereby strengthening the matrix, and it provides dominant pore-filling effects. Nanosilica, after reactions, leaves some kind of coating called lotus coating as shown in Figure **4**, which increases the surface friction and absorption in concrete (Gonzalez *et al*., 2013).

The lotus effect arises from micro and nano scale surface roughness combined with altered surface chemistry, which leads to reduced wettability and restricted moisture ingress into the cement matrix. In nano-modified concrete, nanosilica refines the pore structure, densifies the interfacial transition zone, and limits the growth and penetration of deleterious $Ca(OH)_2$ crystals. These microstructural changes improve interparticle friction and bonding, resulting in enhanced load transfer efficiency under traffic and foundation loads. From a geotechnical perspective, reduced water penetration directly contributes to improved durability, resistance to freeze-thaw damage, and mitigation of moisture-induced weakening in rigid pavement layers and shallow foundation elements. The lotus effect induced surface densification therefore

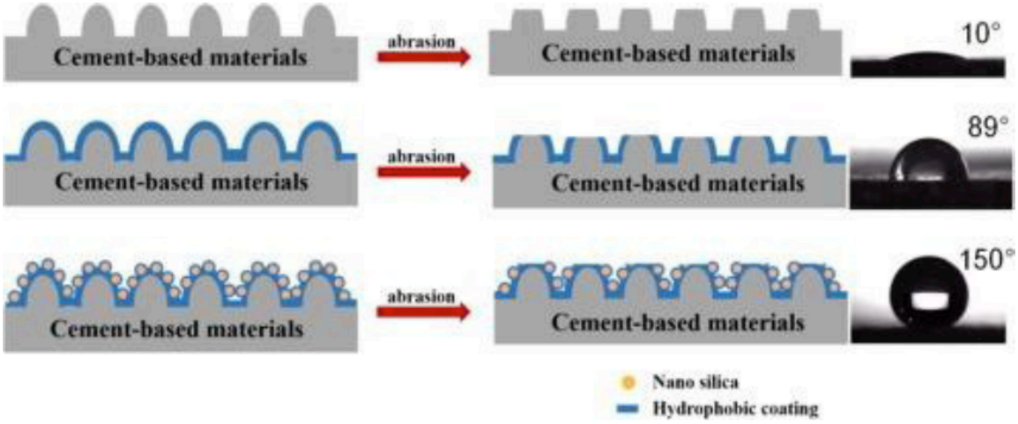

Figure 4: Lotus effect in cement based materials.

plays a critical role in preserving long-term mechanical performance, minimizing environmental degradation, and enhancing the service life of nano-modified cementitious components used in pavement and foundation engineering.

3D texture of the final product also proved the same (Liu *et al*., 2018). Sometimes, nanoparticles act as kernels of the atom and restrict the entry of $Ca(OH)_2$ crystals to penetrate into the concrete. As $Ca(OH)_2$ is a deleterious material for the strength of the concrete so, it must be keep away from the fissures in the concrete (Pacheco-Torgal *et al*., 2013). Conclusively, the nanomaterials have great effects on various properties of the concrete and can be effectively used in pavement construction. These materials can be utilized to serve various functions in the pavement engineering. After all this, still nanomaterials are open for exploration and research. The future researchers can explore the nanomaterials with following aspects (a) nanostructured materials should be synthesized for specific properties and must be prepared for utilizing in the pavements (b) their formation, size and structure etc. can be explored by using appropriate microscopic techniques (c) an interconnection between laboratory and field practitioners must be develop for their proper use and optimization of these materials should be done. In brief, nanomaterials are much capable to enhance the engineering properties of rigid pavements but, their microscopic analysis is still unexplored.

ADVANTAGES OF NANOMATERIALS OVER TRADITIONAL STABILIZERS

The utility of nanomaterials has proved their supremacy over traditional stabilizers in various aspects. In this section, environmental effects, cost analysis and durability effects have been discussed.

Environmental Assessment

Subgrade soils face excessive deformation and slope instability during and after construction. Densification, replacement, drainage and grouting are four conventional subgrade improvement and reinforcement methods. These conventional techniques have some disadvantages too with respect to environment concerns. Grouting is an injection technique, in which, cement paste is grouted by pressure into the soil or rock. This technique effectively improves the strength properties of the loose soil and even rocks. In case of nanomaterials, the finer particles need lower pressure than conventional cement grouting which does not disturb the adjacent natural strata (Mohtar *et al*., 2013; Anders *et al*., 2014; Huang and Wang, 2016; Zahng *et al*., 2017; Zhang *et al*., 2018 a, b). This method is equally effective for highway subgrade and shallow foundations.

As discussed earlier, cement is additional requirement for the effective use of nanomaterials. It serves as binding material in the media. But, recent studies claim that cement production intensifies the carbon emission in the environment. Moreover, cement production consumes huge amount of energy too. Globally, cement production contributes about 5% anthropogenic carbon emission and increasing day by day. Additionally, use of cement at site not only harms the environment but also damages the vegetation and causes bio-chain breakage (White and Brown, 2010). Some chemical grouts *e.g*., sodium silicate, ethoxyline resin etc. have high irritability and cause other skin effects to the labor at site (Kazemian *et al*., 2010). Another disadvantage of chemical slurries can be counted as damage to the environment, dearness, pollution to soil and water. So, their usage is kept limited in field applications. On the other side, nanomaterials are generally non-toxic and non-hazardous to ecology. Therefore, these are considered as safe and environment friendly additives to take advantages in case of weak subgrade and foundations (Lead *et al*., 2018). Nanomaterials are increasingly employed in pavement engineering to enhance performance while supporting environmentally conscious design. When properly engineered and incorporated in controlled dosages, many nanomaterials such as nanosilica, nano-clays, and graphene-based additives exhibit low toxicity and limited environmental mobility, making them suitable for use in asphalt binders and mixtures. These particles improve rheological properties, increasing resistance to rutting, fatigue, and cracking under traffic loads by enhancing binder viscosity and cohesion without introducing harmful chemical residues into the pavement matrix (Yousif and Abed, 2025). Furthermore, nanomaterial-enhanced asphalt can reduce moisture susceptibility and oxidative aging, which extends pavement service life and decreases the need for frequent maintenance and reconstruction, thereby lowering the overall environmental footprint of roadway infrastructure (Afshin and Behnood, 2025; Yousif and Abed, 2025). The ability of these additives to improve recycled asphalt performance also supports sustainable material use in flexible pavements.

Cost Factor

Final product cost depends upon the costs involved in nanomaterial procurement, preparation and testing of specimens, and, any considerable loss involved in the process. Furthermore, external factors *e.g.*, labor wages, machinery maintenance, environmental effects also add-in the overall final product cost (Luo *et al.*, 2007; Bao *et al.*, 2019; Zeng *et al.*, 2019). Although, performance per unit price must be high with respect to handful of nanomaterials. This is a good sign for the use of nanomaterials for subgrade and pavement engineering. A report published in 2005 predicted that by 2020 nanomaterials would become sufficiently widespread and accessible that cost would no longer be a limiting factor (Roco, 2005). Therefore, cost is not expected to be a major obstacle to the widespread use of nanomaterials in subgrade and pavement engineering.

Durability Assessment

Durability is an essential property for all types of pavements; however, its accurate assessment remains challenging for several reasons. First, durability is typically evaluated through laboratory experiments, making it necessary to carefully interpret and translate laboratory results to actual field conditions. Second, durability tests often require long testing durations, which makes their implementation at construction sites nearly impractical due to inevitable disturbances to the field setup. But still, some researches are available on the durability test results. $CaCO_3$ polymer nanocomposites were found to be suitable for aged limestones, as the polymeric nanocomposite significantly improved the compressive strength of the stone (Aldoasri *et al.*, 2017). Nanosilica has improved the durability and reduced the premature failure of concrete bridge deck pavement (Cheng and Shi, 2019). The results showed that nanosilica released $Ca(OH)_2$ after hydration and enhanced the interfaces between slurry and aggregates. The interface hardens the concrete and improves durability. Nanoflyash also improved the durability of concrete (Singh *et al.*, 2019). Nanosilica produced better results than control mix. The pavement durability has also been found improved after mixing the asphalt with nanoclay and nanolime. Thus, it can be interpreted that the nanomaterials improve the durability of soils, concrete, and asphalt mixes.

INTELLIGENT ANALYSIS, MODELING, AND SIMULATION OF NANOMATERIALS

Use of nanomaterials in soils and foundations demands more than empirical testing. Intelligent modeling and simulation can reveal how nano-scale modifications percolate up to macro-scale geotechnical behavior. For instance, mechanical characterization and constitutive modeling of nano-stabilized soil under uniaxial compression develops a constitutive model for nano-stabilized soil (NSS), showing that with increasing nano-stabilizer dosage and curing time, unconfined compressive strength (UCS) increases significantly compared to ordinary stabilized soil or cement-treated soil (Zhang *et al.*, 2023). Such modeling captures both elastic and plastic phases, and the resulting stress-strain curves can be used for design analysis or further simulation under complex load scenarios. On a broader scale, the field of computational materials science as exemplified by research provides approaches to model microstructure evolution, material behavior under stress, and long-term durability, all of which are relevant when soil matrix is modified at nano-scale (Benzerzour *et al.*, 2024). Applying such simulation frameworks to nanomaterial-treated soils allows researchers to predict macroscopic geotechnical parameters (*e.g.*, stiffness, strength, compressibility) based on nano and micro-scale modifications (*e.g.*, pore filling, bonding, microstructure densification). This intelligent, simulation-centric approach reduces reliance on exhaustive experimental campaigns, enables parametric studies (varying dosage, curing, soil type), and supports scalable design recommendations. As computational power and modeling techniques advance, integrating nanoscale effects into geotechnical models could markedly improve the reliability, efficiency, and sustainability of foundation and soil-improvement projects.

Building on the studies discussed above, intelligent geotechnical modeling of nano-stabilized soils can be conceptualized as a unified workflow that links data acquisition, model development, performance prediction, and engineering decision-making. The process begins with experimental and field data generation, including soil index properties, nanomaterial characteristics, dosage, curing conditions, and measured mechanical or durability responses. These datasets form the foundation for constitutive modeling, numerical simulation, and machine-learning-based frameworks that capture the non-linear and scale-dependent effects introduced by nanomaterials.

At the modeling stage, physics-based constitutive models and multiscale simulations translate nano and micro scale mechanisms such as pore filling, particle bonding, and microstructure densification into macroscopic parameters including strength, stiffness, compressibility, and deformation behavior. In parallel, data-driven and machine learning models learn complex interactions among variables, enabling rapid prediction of key performance indicators such as unconfined compressive strength, bearing capacity, settlement response, or slope stability.

These predictive outputs then inform design-level decisions by enabling parameter optimization, sensitivity analysis, and scenario evaluation under varying soil conditions and loading environments. Intelligent models thus serve not as replacements for geotechnical judgment, but as decision-support tools that reduce uncertainty, minimize excessive laboratory testing, and guide performance-based design. This framework illustrates how intelligent systems can systematically integrate nanotechnology into geotechnical engineering practice, bridging experimental insight with scalable, reliable, and future-ready infrastructure design.

AI, MACHINE LEARNING, AND DATA-DRIVEN METHODS INTEGRATING NANOMATERIALS FOR GEOTECHNICAL APPLICATIONS

Recent years have seen a rise of data‑driven, machine learning (ML) methodologies to complement or even replace traditional soil testing and empirical design especially useful when geotechnical systems are enhanced with nanomaterials whose effects can be non‑linear and complex. A rising example of machine learning approach to mitigating geological hazards through geotechnical characterization and stability prediction of nano‑silica‑stabilized slopes can be taken where a large dataset of slope‑stability tests on nano‑silica‑stabilized soils is used to train several ML models (decision tree, support vector regression, random forest, boosting methods, etc.), and the best model outperforms conventional empirical predictions of factor of safety. This demonstrates how ML can integrate multiple variables (nano‑dosage, soil type, moisture, curing, slope geometry) to give robust stability predictions. Similarly, general reviews like The Application of Machine Learning Techniques in Geotechnical Engineering: A Review and Comparison show that ML has been applied across geotechnical tasks, from classification to parameter prediction, offering improved accuracy and efficiency over classical methods (Thapa *et al*., 2025). More recently, in nanosilica and machine learning‑based soil stabilization advancing sustainable and clean technologies for resilient infrastructure, researchers treated fine‑grained soils with nanosilica and used deep‑learning models to predict unconfined compressive strength (UCS) after curing, achieving high fidelity in predictions, and thereby enabling optimization of nano‑dosage for different soil types and use‑cases (Shao *et al*., 2023; Gao, 2024). Data‑driven methods reduce the need for exhaustive lab testing, accelerate design cycles, and allow incorporation of complex interactions (*e.g*. nano‑material effects, curing time, soil heterogeneity, environmental conditions). With explainable ML (*e.g*. SHAP values, feature importance), engineers can also understand which variables (such as nano‑dosage, soil density, moisture) drive performance, a key step toward practical guidelines and design recommendations. As databases grow and ML/AI integration becomes standard, combining nanotechnology with data‑driven geotechnical engineering can lead to sustainable, high‑performance soils and foundations bridging cutting‑edge materials science with robust, real‑world engineering practice (Thapa and Ghani, 2025).

CONCLUSIONS

This study demonstrates that nanomaterials offer a powerful and sustainable alternative to conventional stabilizers utilized in subgrade and pavement engineering. The inclusion of nanomaterials significantly enhances the physicochemical and mechanical properties of soils through pore filling, particle bonding, and accelerated hydration and pozzolanic reactions, leading to a denser and stronger soil matrix. In flexible pavements, nanomodified asphalt shows superior resistance to rutting, fatigue, moisture damage, and thermal aging. In rigid pavements, nanosilica and related additives improve the interfacial transition zone, refine the microstructure, and, enhance strength and long-term durability. From an environmental perspective, nanotechnology requires lower material consumption, reduces carbon footprint, and offers safer alternatives to chemical stabilizers. Economically, the high performance-to-cost ratio makes nanomaterials a viable option for large-scale infrastructure projects. With the integration of intelligent modeling, machine learning, and data-driven design methods, nanotechnology is poised to play a crucial role in next-generation, resilient, and sustainable geotechnical and pavement systems.

Lifecycle assessment (LCA), carbon footprint quantification, and comparative cost benchmarking have not been undertaken in this study; however, can represent important directions for future research on intelligent nanotechnology applications in pavement engineering. While existing evidences suggest that nanomaterials may reduce material consumption and enhance durability, their net environmental and economic benefits depend strongly on factors such as synthesis route, dosage, transportation, construction practice, and service life extension. Future studies should adopt standardized LCA frameworks, carbon accounting methods, and region-specific cost models to objectively evaluate the sustainability and scalability of nano-stabilized subgrades and pavements. Integrating such assessments with intelligent modeling and data-driven optimization would enable more informed, performance-based, and sustainable design decisions for next-generation infrastructure systems.

CONFLICTS OF INTEREST

Author declares that there is no conflict of interests concerning the publication of this manuscript.

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