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Effect of Nano Materials on Geotechnical Properties of Expansive Soils: A Review

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ABSTRACT

Expansive soils are responsible for extensive infrastructure damage worldwide, prompting the urgent search for innovative, sustainable stabilization methods. Nanomaterials have emerged as a promising next-generation solution capable of addressing both performance and environmental challenges. This review investigated the use of nanomaterials such as nano-silica, nano-alumina, nano-copper, nano-MgO, and nano-calcined clay and terrasil, and a combination of nanomaterials with lime or cement (hybrid) as sustainable stabilizers. It was found that plasticity index (PI) decreases by 20-60%, optimum moisture content decreases of 10-12%, and maximum dry density increases of 5-10% for ≤1% nonadditive. Swell potential and swell pressure typically reduced by 20-30% or more at dosages ≤1-1.5%, while hybrid mixes achieve even higher reductions. Strength gains were particularly significant: unconfined compressive strength (UCS) commonly doubles in the short term and exceeds 5 times untreated values with long-term curing, reaching up to 6 times with hybrid stabilization. Similarly, soaked CBR values improve by about 2 times with nanomaterials alone and up to 5-6 times with hybrid systems. These mechanical enhancements were supported by microstructural evidence showing pore filling, formation of cementitious gels (CSH, CAH, MSH, CASH), and surface coatings that densify soil, strengthen particle bonding, and reduce water ingress. Performance was strongly dosage- and material-dependent, with excessive amounts sometimes leading to agglomeration and reduced efficiency. Overall, findings confirmed that nanomaterials, especially when combined with lime or cement, provided a reliable, sustainable, and long-term stabilization approach, offering substantial improvements in expansive soil behavior and geotechnical infrastructure performance.

1. INTRODUCTION

Expansive soils are commonly found in arid and semi-arid regions, where annual evaporation exceeds rainfall or where short rainy periods are followed by prolonged droughts. These climatic conditions cause repeated dry–wet cycles, leading to significant volume changes. Expansive soils are typically rich in clay minerals, especially montmorillonite, and are characterized by a liquid limit exceeding 50% and a plasticity index above 25%. Their swelling potential is strongly influenced by the specific surface area of the clay minerals [1]. Swelling occurs when water is adsorbed on the outer surfaces and within the interlayer spaces of clay minerals, forcing the plates apart as moisture increases [2]. These swelling and shrinkage cycles cause distress in lightly loaded structures such as buildings, pavements, and pipelines, resulting in cracks, differential settlements, rutting, and reduced service life [3,4]. For example, Zornberg and Roodi [5] documented extensive longitudinal cracking and rutting in Texas roadways, while residential buildings in Colorado have shown structural cracking within two to three years of construction. Economically, the impact is severe: in

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the United Kingdom, expansive soils are the costliest geohazard, causing approximately USD 3.5 billion in damages over the past decade [6]. In the United States, annual losses exceed USD 9 billion, with more than USD 4.55 billion attributed to road and street damage alone [7, 8]. Therefore, it is important to conduct an appropriate ground improvement to mitigate the issue before it happens.

Mitigation typically involves ground improvement; however, mechanical compaction is often ineffective in controlling swelling because densification alone cannot address the inherent mineral reactivity. Chemical stabilization using lime or cement is more widely used, improving strength and reducing swell potential [9-11]. Despite its effectiveness, cement-based and lime-based stabilizations are costly and environmentally unsustainable due to the high CO_2 emissions from cement and lime production [12, 13]. In addition, most of these conventional chemical additives may contribute to global warming because they require high energy demand [14]. This has led to increasing interest in more sustainable and high-performance alternatives [15, 16]. Nanotechnology has advanced rapidly in recent years and is increasingly being applied across diverse scientific and engineering fields, notably in construction materials and the stabilization of problematic soils such as expansive soil [16-18]. Nanomaterials including zero-dimensional nanoparticles (e.g., nano-silica, nano-alumina), one-dimensional fibers (e.g., carbon nanotubes), and two-dimensional sheets (e.g., nano-clay, graphene nanosheets) possess exceptionally high surface area-to-volume ratios and unique physicochemical properties [19, 20]. Even though, certain challenges remain, including uncertainties regarding long-term performance, difficulties in controlling application dosage under field conditions, and potential economic limitations, incorporating even a small quantity of nanomaterials into soils can markedly alter their physical and chemical characteristics because of their exceptionally high specific surface area. This makes nanotechnology-based treatment approaches both environmentally friendly and cost-effective [19, 21].

Although there has been extensive research on nanomaterials for non-expansive soils [22-29], the only known review addressing expansive soils is by Suresh and Murugaiyan [30], which was limited to swelling potential and unconfined compressive strength, and covered only a small number of studies. Therefore, a broader and more comprehensive synthesis is needed to fully understand the influence of nanomaterials on the engineering and microstructural properties of expansive soils. This review addresses that gap by examining a wide range of properties including index (i.e. plasticity index (PI)), compaction characteristics (optimum moisture content (OMC), and maximum dry density (MDD)), unconfined compressive strength (UCS), California Bearing Ratio (CBR), and microstructural changes, when expansive subgrades are stabilized with different nanomaterials. The findings are expected to provide valuable insights into the effectiveness, limitations, and environmental benefits of nanomaterials, positioning them as promising next-generation stabilizers for mitigating the global challenges posed by expansive soils.

2. EFFECT OF NANOMATERIALS ON SOIL PLASTICITY OF EXPANSIVE SOILS

According to Casagrande, soil classifies as high plasticity soil (CH) or known as expansive soil, when liquid limit (LL) and plasticity index (PI) of soil exceed 50% and 25%, respectively. Plasticity, quantified through the Atterberg limits, is a key indicator of an expansive soil's potential to undergo volume changes with moisture variation. A higher PI is generally associated with greater swelling potential due to the dominance of active clay minerals such as montmorillonite [31]. Reducing PI through stabilization directly decreases the soil's capacity to absorb water and swell, thereby mitigating damage to overlying structures.

In this review, the effect of nanomaterials on PI have been navigated. Figure. 1 presents the collected results from literature to visually illustrate the effect of different nanomaterials on the soil PI. For example, Taha and Taha [32] investigated the effects of nano-alumina (0.05–0.3% by dry weight) and nano-copper (0.15–0.7%) on the plasticity of expansive soil. Both additives produced modest reductions in PI by filling micropores, binding clay particles, and limiting water adsorption. While nano-alumina caused a slight decrease, higher contents of nano-copper achieved greater PI reduction due to its larger surface area compared to nano-alumina. In addition, Naval et al. [33] studied the effect of nanomaterials (nano-MgO and nano-alumina) with different percentage ranged between 0.5 to 2.0% on the soil plasticity of an expansive soil. Results showed that both additives caused to reduce PI significantly and the maximum reduction was reported at 2% nanomaterial addition. Furthermore, Pusadkar et al. [34] performed a study to investigate the impact of a nano-copper to PI. It was found that the soil plasticity increased as the nano-copper increased up to 1.5% nanomaterial then it decreased to reach slightly less value than the natural soil at 2.5% addition. In another study, Al-Khazzaz et al. [35] examined the effect of nano-MgO on expansive soil and found that the PI increased with nano content up to 0.75%, reaching 35% about 1.35 times higher than untreated soil. At 1.0% content, the

PI declined slightly but remained above that of the untreated samples.

Nanomaterials have also been applied in combination with conventional stabilizers. For example, Rangaswamy and Mohan [15] reported effect of nano-terrasil with a dosage ranged between 0.03% and 0.05% in combination with 1.0% cement on PI of expansive soil. Results showed that PI decreases with the nano-additive and the maximum reduction in PI reported at an additive of 0.045%. In a related study, Abdulamer and Daham [36] investigated nano-calcium carbonate (0.3–1.5%) combined with 4% lime and found that the PI of expansive soil decreased from 31% to below 13% at 0.7% dosage. This demonstrates that even small amounts of nanomaterial can significantly enhance soil plasticity characteristics. Additionally, Al-Swaidani et al. [37] examined three expansive soils with PI values of 29–42% using nano-calcined clay and nano-lime. Nano-calcined clay alone reduced PI by 40–60% at 1–2% dosage, while the combined treatment of 2% nano-calcined clay with 0.6% nano-lime achieved an even greater reduction, confirming the synergistic effect of blended nanomaterials.

As illustrated in Figure. 1, the reviewed studies collectively demonstrate that nanomaterials exert diverse and often contradictory effects on the plasticity of expansive soils, governed by their intrinsic properties and interaction mechanisms. However, the figure illustrates that the PI showed a general trend of reduction with increasing nano-content, although the rate of decrease varied with the type of nanomaterial. Nano-alumina, nano-copper, and nano-calcined clay produced significant reductions in PI, with values dropping from around 30–40% to below 20-25% at contents of 1% or less. Among these, the combination of nano-calcined clay with nano-lime exhibited the greatest improvement, reducing PI to as low as 5–8%, indicating a strong stabilizing effect. Similarly, the inclusion of nano-Terrasil with cement demonstrated a steep decline in PI, highlighting the effectiveness of nanomaterials in enhancing cementitious reactions. In contrast, nano-MgO and nano-calcium carbonate produced more moderate or variable responses, suggesting soil-specific interactions. Overall, the results confirm that nanomaterials, particularly when combined with small amount of lime or cement, substantially reduce soil plasticity, and improving engineering performance.

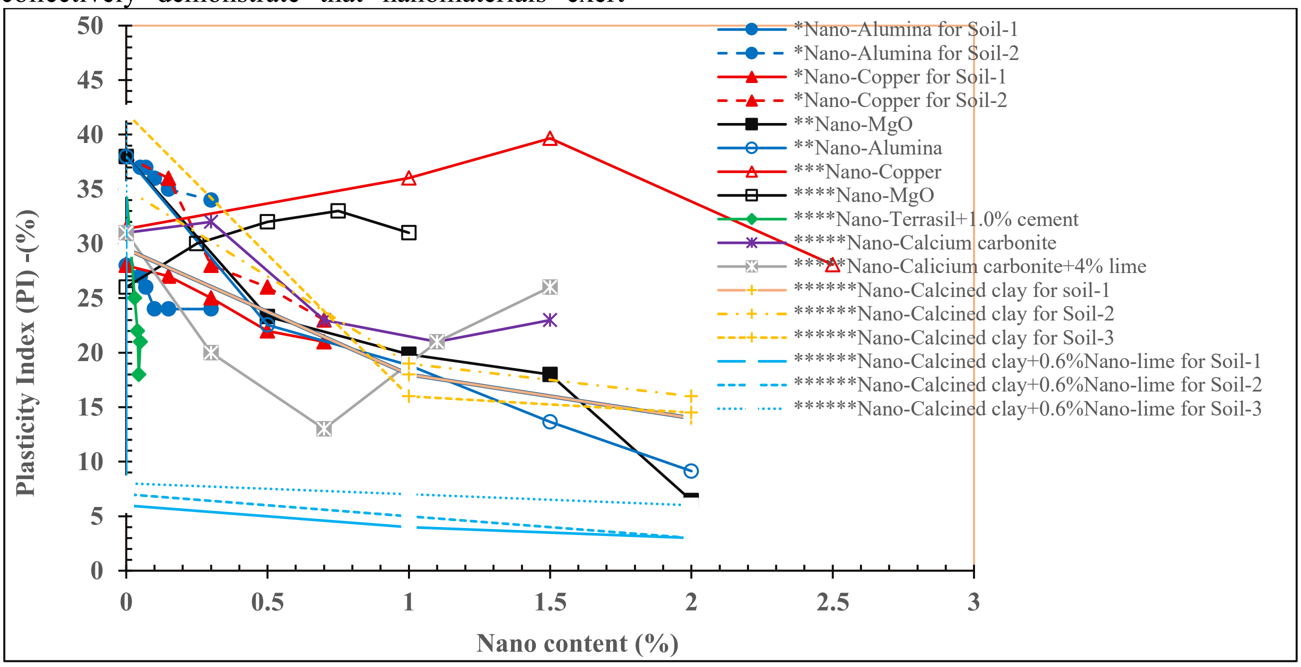

Figure 1. Effect of nanomaterials on plasticity index (PI) of expansive soils

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3. EFFECT OF NANOMATERIALS ON PHYSICAL PROPERTIES OF EXPANSIVE SOILS

The compaction characteristics of expansive soils, particularly optimum moisture content (OMC) and maximum dry density (MDD), are critical for geotechnical stability, as they influence soil strength, and swelling potential. Traditional stabilization methods often face limitations in balancing moisture control and density enhancement, prompting researchers to explore nanomaterials as innovative modifiers. This review synthesizes findings from studies employing diverse nanomaterials: including nano-alumina, nano-copper, nano-MgO, nano-Silica, Nano-Terrasil and hybrid nano lime, nano-calcined clay, and hybrid nano-lime to optimize compaction curves. Results demonstrate that nanomaterial type, dosage, particle size, and interaction mechanisms (e.g., pore filling, pozzolanic reactions, hydrophobic effects) govern their efficiency [15].

Figures 2 and 3 present respectively, the results of the OMC and the associated MDD for different nanomaterials. For instance, nano-copper enhance MDD through densification, while nano-MgO and nano-calcined clay reduce OMC via chemical stabilization. Hybrid approaches, such as combining nano-calcined clay with nano-lime or nano-Terrasil with lime reveal the change in moisture content and structural reinforcement. These insights underscore the potential of nanomaterials to compaction properties, though outcomes depend critically on soil composition and application-specific goals. For instance, Taha and Taha [32] examined the compaction behaviour of three different expansive soils treated with nano-alumina and nano-copper. Nano-alumina reduced OMC most effectively at 0.1% in clay-rich soils, while nano-copper achieved the highest MDD improvement of 10–12% at 0.7%. The study suggests nano-alumina is best suited for high-clay soils due to its chemical interactions, whereas nano-copper is more effective for enhancing soil density. In related study, Naval et al. [33] investigated expansive soil stabilization using nano-MgO and nano-alumina (0.5–2.0%). OMC increased up to 1.0–1.5% dosage due to flocculation, then declined at 2.0% from density effects. Both additives improved MDD by 8–10%, with nano-MgO slightly more effective. At 1.5% nano-MgO, OMC decreased by 7% and MDD increased by 14.3%, indicating an optimal balance for practical stabilization. The observed improvements can be linked to the pozzolanic reactions of nano-MgO, which generate cementitious compounds, and the pore-filling properties of nano-Alumina, which reduce void ratios. Similarly, Pusadkar et al. [34] evaluated nano-copper (0–1.5%) for expansive soil stabilization and found a steady OMC reduction of 8–10% and a linear MDD increase of 5–9%. The optimum dosage was 1.5%, where pore filling and particle rearrangement minimized water demand while enhancing density, confirming nano-copper's effectiveness as both a moisture regulator and densifier for subgrade applications.

Nanomaterials have also been tested in combination with traditional stabilizers. For instance, Pokkunuri et al. [38] studied Terrasil and lime (0–1%) with and without 3% lime on three expansive soils (initial OMC 9.6–14%, MDD 1.821–1.961 g/cm³). Nano-stabilizers outperformed lime, reducing OMC by 15–29% and increasing MDD through pore space reduction, whereas lime alone provided marginal densification and sometimes decreased MDD. The results highlight that 1% nano-stabilizer offers superior short-term compaction improvements compared to traditional lime. In another experimental investigation, Al-Swaidani et al. [37] studied the effects of nano-calcined clay alone and in combination with nano-lime. The use of nano-calcined clay alone at 1-2% reduced OMC by 10-15% and increased MDD by 5-7% through pore-filling and pozzolanic activity. When used together (with 0.6% nano-lime), the conflicting effects were neutralized, producing compaction properties close to natural soil. This complementary behavior demonstrates that the hybrid stabilization can be tailored to offset undesired effects of individual nanomaterials.

The Figures 2 and 3 collectively demonstrate that nanomaterial addition significantly influences the compaction behaviour of expansive soils, with distinct trends for OMC and MDD. The OMC responses are material-specific: nano-alumina and nano-copper caused minimal change of approximately (15–16%), while nano-MgO and one dataset of nano-alumina showed an initial rise in OMC due to hydration reactions before declining at higher contents, and nano-calcined clay started with high OMC of approximately (30%) but decreased steadily as dosage increased, reflecting improved densification. The most effective OMC reductions were achieved with combined stabilizers such as nano-calcined clay with lime and nano-Terrasil with lime, lowering OMC to 8–12%. In terms of MDD, most nanomaterials enhanced soil density, with nano-alumina, nano-copper, and nano-MgO producing the highest increases (>2.0 g/cm³), while nano-calcined clay and its lime combination yielded gradual but consistent improvements. Terrasil with lime also achieved notable gains, particularly for treated soils, underscoring synergistic effects. Overall, nanomaterials enhance compaction by reducing pore spaces, refining particle arrangement, and fostering stronger interparticle bonding, thereby improving soil densification and stability.

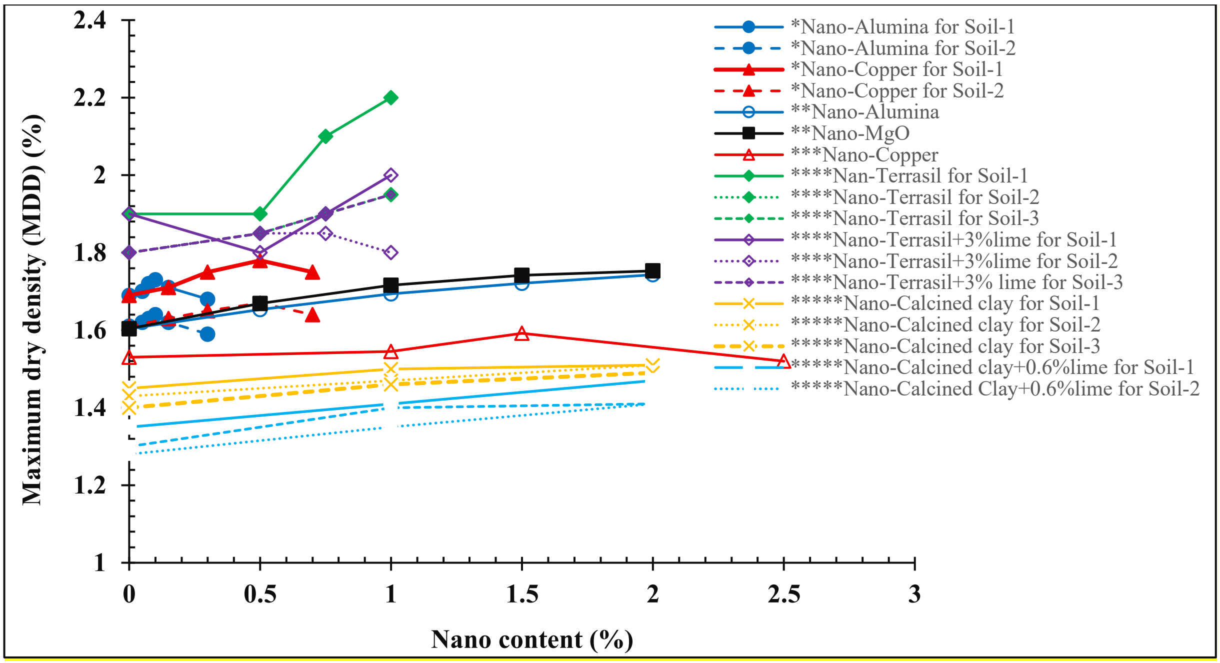

Figure 2. Effect of nanomaterials on optimum moisture content

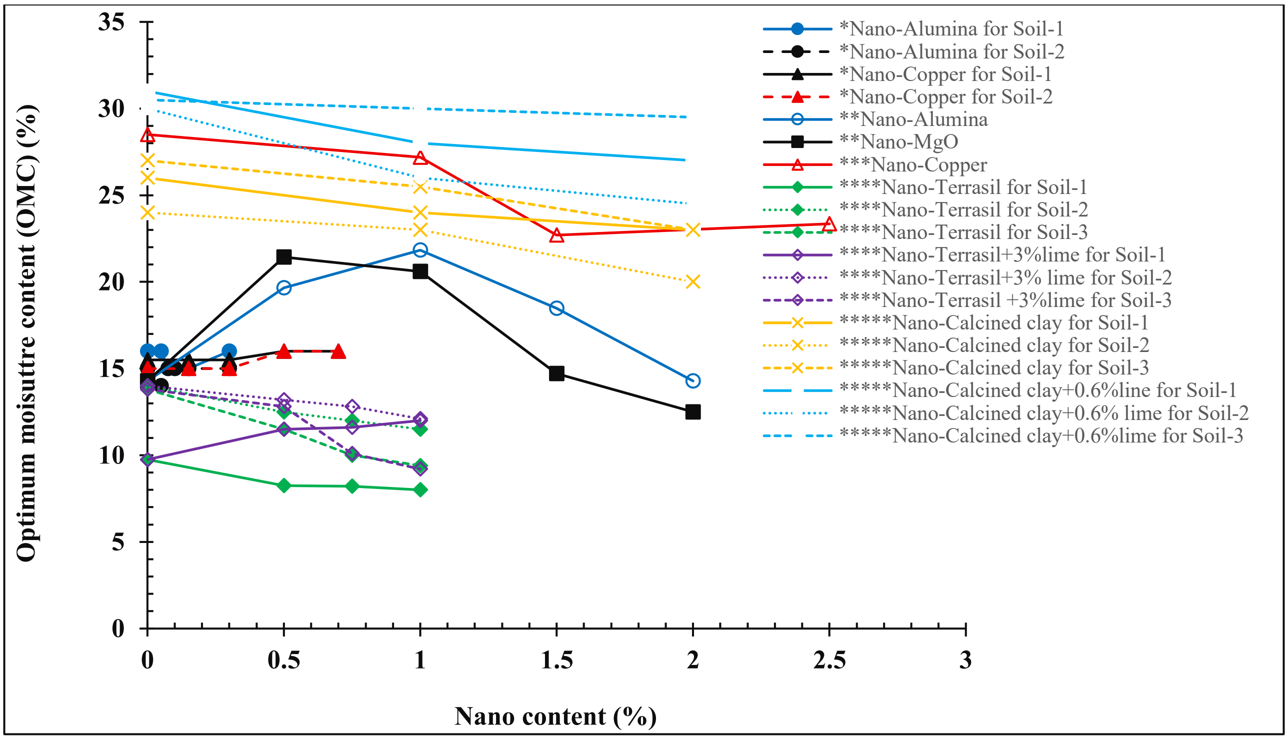

Figure 3. Effect of nanomaterials on maximum dry density (MDD) of expansive soils

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4. Effect of Nanomaterials on Mechanical Properties of Expansive Soils

4.1 Swelling properties

4.1.1 Swell potential

Figure 4 illustrates the swell potential behaviour for different nanomaterials treated expansive soils. Such findings have been collected from literatures to assess the effectiveness of using nanomaterials in solving swelling issue of expansive soils. Rincón-Morantes [22] and Suresh and Murugaiyan [30] found that nanomaterials cause to decreasing swelling potential where nanomaterials become a very thin layer between particles that prevent water interring in the voids as waterproof. Swell potential is calculated using equation (1).

$$SP\ (\%) = (2.16 \times 10^{-3})(PI)^{2.44} \quad (1)$$

Where:

SP: Swell potential

PI: Soil plasticity index

A study conducted by Taha and Taha [32] investigated soil stabilization of three expansive soils using nano-alumina (0–0.3%) and nano-copper (0–0.7%). Both nanomaterials reduced expansion by nearly 50%, with nano-alumina performing best at 0.1% due to optimal void filling, and nano-copper showing progressive improvement up to 0.5% via bonding effects. The study suggests nano-alumina for cost-effective low-dosage applications and nano-copper for scalable stabilization. These findings suggest practical applications: contractors working with swelling soils might prefer nano-alumina's cost-effective low dosage, whereas projects requiring graded stabilization could benefit from nano-copper's scalable effects. In related study, Naval et al. [33] evaluated nano-MgO and nano-alumina (0.5–2.0%) for stabilizing expansive soils. Results showed that increasing nano content progressively reduced swelling potential, reaching near-zero at 2.0%, indicating that these additives act both as particle aggregators and cementitious precursors to create a more stable soil structure. Further, Abdelrahman et al. [39] investigated the changes in microstructural, physical, and mechanical properties of expansive soils when treated with nanoscale additives: nano-silica, nano-metakaolin, and nano-cement. The additives were tested at concentrations ranging from 0% to 4%. Mechanical evaluations showed that marginal reduction in swell potential along with the nano-additive content. Moreover, Al-Khazzaz et al. [35] investigated the effects of nano-MgO dosage (0.25-1.0%) on the swelling characteristics of expansive soils. The untreated control specimens exhibited maximum swell potential (6%), while nano-MgO incorporation significantly mitigated swelling, with optimal performance observed at 0.25% concentration. Beyond this threshold, a slight rebound in swell potential occurred, though values remained substantially lower than untreated soil. Similarly, Mosa et al. [40] investigated MgO dosages (0.1–1.5%) for stabilizing expansive soils in road subgrades. Swelling steadily decreased with increasing MgO, reaching a minimum of 0.46% at 0.7% dosage (versus 2% for untreated soil). Beyond this optimal point, swelling increased again, rising to 1.55% at 1.5% MgO, highlighting a clear optimal dosage for minimizing soil expansion. Furthermore, Hirwo et al. [41] demonstrated that effect of nano-silica (1-3%) on swelling potential of an expansive soil, with dry-mixed showing progressively lower swelling potential as nano-silica content increased - from 29.73% (untreated) to 10.03% (3% nano-silica). In is important to note that among others, Al-Khazzaz et al. [35] is the only study considers the curing time effect on swell potential. Curing time emerged as a critical factor, demonstrating an inverse relationship with swell potential across all treatments. The 0.25% nano-MgO specimens achieved maximal swell reduction (31.7%) after long-term curing time extended curing (56 days), whereas higher concentrations (0.5–1.0%) showed progressively diminished effectiveness (11.7–3.3% reduction). These trends suggest two competing mechanisms: at optimal dosage (0.25%), nano-MgO facilitates complete clay particle coating and pozzolanic reactions, while excessive concentrations may induce particle agglomeration, reducing treatment efficiency.

Nanomaterials have also been tested in combination with traditional stabilizers. For example, Pokkunuri et al. [38] investigated the stabilization of three expansive soils using Terrasil nanomaterials (1%) with and without lime (3%). Results showed that Terrasil alone reduced swell potential significantly, while the addition of 3% lime completely eliminated swelling. This indicates that lime's pozzolanic reactions can surpass the pore-filling and hydrophobic effects of nanomaterials in highly swelling, montmorillonite-rich soils. Further, Al-Swaidani et al. [37] reported that both nano-calcined clay (1–2%) and nano-lime (0.6%) reduced swelling individually, with greater reduction achieved when combined. Overall, nanomaterials mitigate expansive soil behaviour through mechanisms like pore-filling, cation exchange, pozzolanic reactions, and hydrophobic effects. Nano-MgO (0.25–0.7%) and nano-silica (2–3%) proved particularly effective, lowering swelling potential by up to 77%. Hybrid treatments with lime further enhance stabilization, though efficacy depends on dosage and soil type, with excessive concentrations causing agglomeration.

Figure 4 illustrates the reduction in swell potential of expansive soils with increasing nanomaterial content, highlighting the effectiveness of different nano-additives. All nanomaterials markedly reduce swelling compared to untreated soils, with the most dramatic improvements occurring at low dosages (≤1%). For instance, untreated soils with swell potentials above 30–70% drop to below 10% when treated with 0.5–1% nano-silica, nano-Terrasil, or nano-calcined clay, while hybrid combinations (e.g., nano-Terrasil + 3% lime or nano-calcined clay + 0.6% lime) nearly eliminate swelling (<2%), demonstrating strong synergistic effects. Beyond the optimum range, additional nano content yields minimal further reduction, indicating dosage efficiency is key. Overall, the data confirm that nanoscale additives, particularly when paired with lime, substantially mitigate expansive soil swelling by reducing porosity, enhancing cementitious bonding, and limiting water absorption.

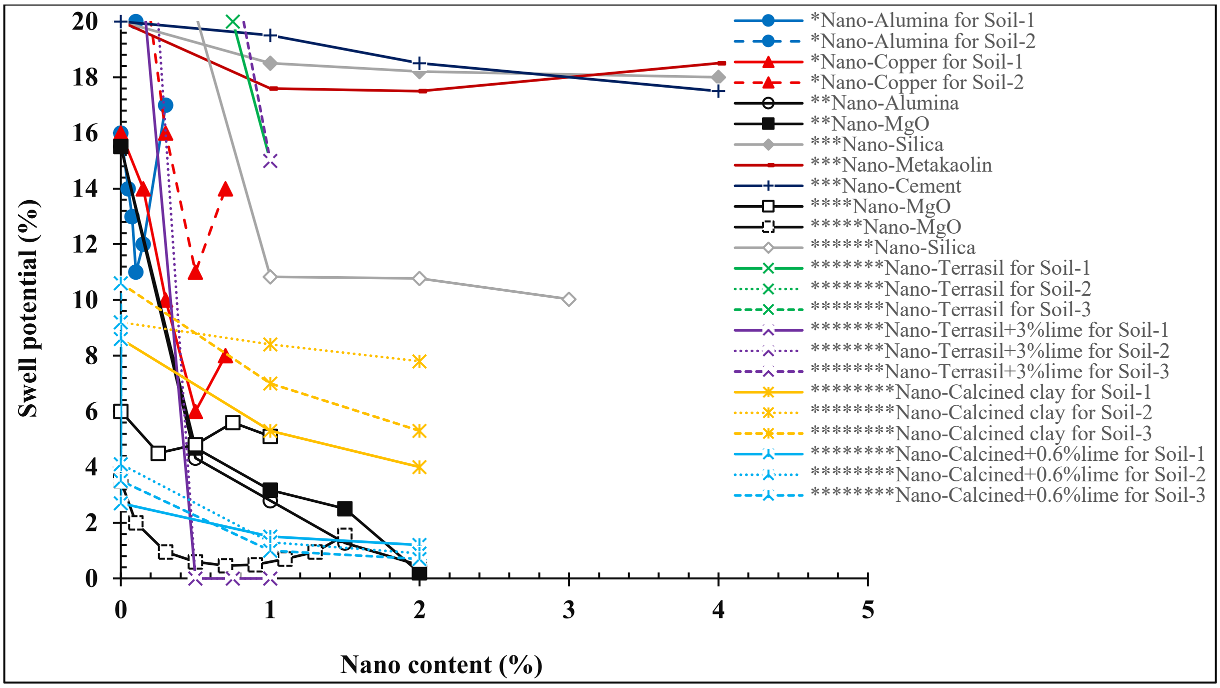

Figure 4. Effect of nanomaterials on swell potential of expansive soils
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4.1.2 Swell pressure

Swell pressure is defined as the pressure required to prevent a saturated expansive soil from swelling when its volume is kept constant [31]. It is a critical parameter because it directly influences foundation design, pavement performance, and retaining structure stability in expansive soil regions. High swell pressures can exceed the bearing capacity of light structures, leading to heaving, cracking, and serviceability failures [3]. Including this definition and its significance will help readers understand why reducing swell pressure is a key objective in soil stabilization studies. Effect of nano materials on swell pressure of expansive soil have been covered by many researchers and the findings have been collected and plotted on one graph for performance comparison purposes as shown in Figure 5. This figure assesses the efficiency of various nano-additives for mitigating the swelling pressure of expansive soils. This includes the effect of nano-silica, nano-metakaolin, nano-cement, nano-copper, nano-MgO. In addition, a combination of nano-calcined clay and nano-lime on soil swelling characteristics of expansive soils. For instance, Abdelrahman et al. [39] investigated nano-silica, nano-metakaolin, and nano-cement at 1–3% dosages. Nano-silica and nano-metakaolin reduced soil swelling pressure by up to 27% by forming tight, water-repelling barriers, while nano-cement increased swelling by 8–12% due to hydration-induced loosening. These results suggest that nano-silica and nano-metakaolin provide effective and safer stabilization for expansive soils, balancing pore-filling and moisture resistance. Further, Al-Khazzaz et al. [35] used nano- MgO to treat expansive soil. It was found that untreated soil maintained their full 200 kPa swelling pressure, treated soil showed significantly better behavior, with swelling pressures dropping to 160 kPa. Furthermore, Pusadkar et al. [34] evaluated the swelling pressure of expansive soil treated with 1.5% nano-copper. The untreated soil exhibited a swelling pressure of 120 kPa, which decreased by 22% with nano-copper treatment. This demonstrates that nano-copper is an effective additive for stabilizing expansive soils, particularly when conventional methods are insufficient. Regarding to curing time, Al-Khazzaz et al. [35] found that longer the curing time (up to 56 days) with nano-MgO can decrease the swell pressure to 130-140 kPa. Such research revealed that nano-MgO works best as a precise "dose" (0.75%) rather than in large quantities, offering engineers a targeted solution that improves with time for long-term soil stabilization.

In a combination of nanomaterials with transitional stabilizers, Al-Swaidani et al. [37] used two nano-materials: nano-calcined clay and nano-lime for treating expansive soil. While nano-calcined clay alone (1-2%) did a decent job reducing swelling, the real magic happened when they joined forces by adding only 0.6% nano-lime. In synthesis, most research indicates that nanomaterials, particularly nano-silica, and nano-alumina can reduce swell pressure by more than 30%, depending on soil mineralogy, dosage, and curing time [32, 35]. Common trends include a steeper initial reduction at low dosages (1-2%), with diminishing returns beyond 4-5%. In conclusion, nanomaterials reduce swell pressure through several physicochemical mechanisms: Pore structure refinement of nano-silica fill micropores, reducing available space for water adsorption. Diffuse double layer (DDL) compression-High surface reactivity of nanoparticles neutralizes clay particle surface charges, leading to reduced interparticle repulsion and swelling tendency [15]. Formation of cementitious gels-in reactive clays, nanoparticles promote the formation of CSH and CAH gels, which bind clay particles and reduce their expansivity [19]. Surface coating effects, some nanomaterials, such as nano-MgO, form protective coatings on clay particles, limiting moisture ingress and volumetric changes.

Figure 5 illustrates the behaviour of swell pressure for various nanomaterials such as nano-silica, nano-metakaolin, nano-MgO, nano-copper, and combinations like nano-calcined clay with nano-lime. It shows that swelling pressure reduce effectively by 20–30% or more, depending on dosage, curing time, and soil type. Mechanisms include micropore filling, surface charge neutralization, formation of cementitious gels, and protective particle coatings, which collectively limit water adsorption and interparticle repulsion. Notably, nano-silica and nano-metakaolin consistently perform better than nano-cement, which may increase swelling due to hydration-induced loosening, while precise dosing of nano-MgO or combined nanomaterials enhances long-term stabilization [35]. Overall, nanomaterial additives offer targeted, efficient, and reliable approaches to mitigate expansive soil swell pressure, improving soil performance.

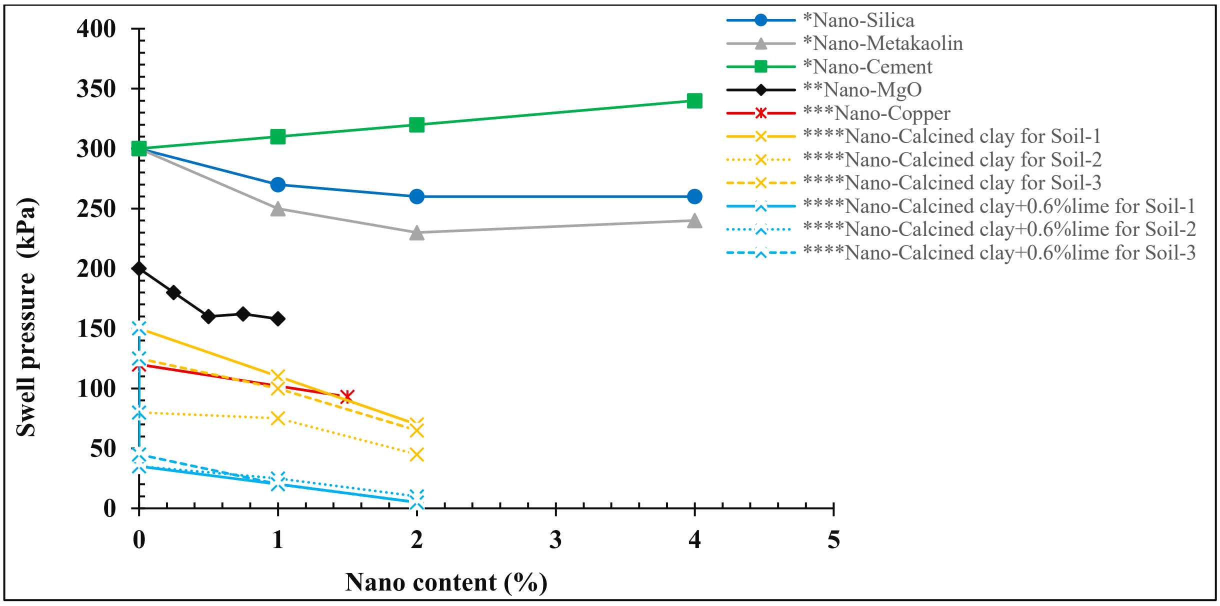

Figure 5. Effect of nanomaterial on swelling pressure of expansive soils
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4.2 Strength properties

4.2.1 Unconfined compression strength (UCS)

Figure 6 showed the collected results from literature to assess the effect of different nanomaterials on the unconfined compressive strength (UCS) of expansive soils focussing on short-term curing time (1 to 7 days). For example, Pusadkar et al. [34] used nano-copper to improve the strength of an expansive soil. It was found that the UCS of untreated soil was 151.75 kN/m², and when adding 1.5% nano-copper, the soil strength became nearly three-time stronger (420.8 kN/m²). In similar study, Shang and Fu [42] studied nano-enhanced soil stabilization, testing nano-alumina and nano-silica (0.5-2%) on expansive soils. The results revealed an optimum zone for each: nano-alumina peaked at 1.2% (316 kPa strength, 58%

improvement), while nano-silica at 1.5% exhibit a strength of 363 kPa (68% improvement). Further, Raj and Toshniwal [43] investigated Terrasil, a nanomaterial added at 0.7–1.2% to expansive soil. At 1.2%, Terrasil increased soil strength from 200 kPa to 325 kPa (>60% improvement) by filling voids and binding particles without over-clogging, highlighting its effectiveness as an optimal nanoscale stabilizer for enhancing soil mechanics. Furthermore, Hirwo et al. [44] showed that adding 1–3% nano-silica to expansive soil increased UCS from 248 kPa (untreated) to 382, 447, and 474 kPa at 1%, 2%, and 3%, corresponding to 54–91% strength gain. The sharp improvement at low dosages reflects nano-silica's high reactivity, while the slower gain beyond 2% suggests an approaching optimum. Strength enhancement arises from pozzolanic CSH gel formation and microvoid filling, which densify the soil structure.

On the other hand, Pokkunuri et al. [38] experimentally evaluated Terrasil nanomaterial alone and combined with 3% lime for stabilizing three expansive soils. Optimal performance occurred at 1% Terrasil, which reduced interparticle porosity, while lime enhanced pozzolanic cementation. The study highlights lime's stronger stabilizing effect and identifies the 1% Terrasil + 3% lime combination as a promising hybrid approach for maximizing soil strength in geotechnical applications. In addition, the results of James et al. [45] indicate that the addition of nano-alumina to lime-stabilized soil significantly influences strength development. With 4.5% lime incorporation of 0.5% nano-alumina yielded the highest improvement, reaching 135 kPa. However, higher dosages (≥1%) resulted in lower or fluctuating strengths, suggesting that 0.5% is the optimum dosage for effective stabilization. Further, according to Abdulamer and Daham [36], the inclusion of nano-calcium carbonate in lime-stabilized soil (4% lime) improved strength, with UCS increasing from 25 kPa in the untreated state to a peak of 45 kPa at 0.7%. Beyond this range (≥1.1%), UCS values declined or fluctuated, indicating that excessive nano-calcium carbonate may hinder reaction efficiency due to particle agglomeration. Thus, the optimum content lies around 0.7%. Furthermore, Rangaswamy and Mohan [15] reported that the addition of nano-Terrasil with 1% cement markedly improved soil strength, with UCS increasing from 50 kPa in the untreated sample to a peak of 100 kPa at 0.045% dosage. However, at 0.05% the UCS dropped to 80 kPa, indicating that overdosing may reduce efficiency due to particle agglomeration

Strength development was evident at all curing periods. Therefore, an optimum additive content was plotted with curing time under laboratory temperature. for different nanomaterials to visually illustrated the curing time effect on UCS as shown in Figure 7. The results in the Figure clearly demonstrate that the effect of curing time on UCS strongly depends on the type of nanomaterial used. The soil treated with 1.5% nano-copper achieved the highest strength, increasing from about 400 kPa to nearly 650 kPa at one-week, and stabilizing around 660–670 kPa at 28 days, representing a rapid of 65% gain in just 7days followed by a plateau. A similar but slightly lower trend was observed for 0.5% nano-alumina combined with 4.5% lime, where UCS rose from nearly 135 kPa to 360 kPa in 7days to 600 kPa at 28 days, showing that lime–alumina reactions rapidly enhanced cementitious bonding. In comparison, 0.045% nano-Terrasil with 1% cement showed moderate improvement, increasing from 110 kPa to nearly 220 kPa at 28 days and 230 kPa at 90 days, indicating that hydration and hydrophobic effects were beneficial but limited by the low cement dosage. Much lower strengths were recorded for 0.7% nano-carbonite calcium, which increased from 35 kPa to 120 kPa at 28 days, and for 0.7% nano-carbonite calcium with 4% lime, which improved to 150 kPa at 28 days. These results confirm that nano-copper and nano-alumina are the most effective stabilizers, producing UCS values of 600–670 kPa at 28 days, almost 5–6 times greater than untreated expansive soil, whereas nano-carbonite compounds contributed only marginally. The overall pattern highlights that most strength gain occurs within the first 28 days due to rapid pozzolanic and hydration reactions, after which improvements plateau as reactive products are consumed.

In summary, Nanomaterials markedly improve the UCS of expansive soils, with performance varying by type and dosage. Nano-copper (1.5%) achieved the highest strength, nearly tripling UCS to 670 kPa at 28 days, while nano-alumina with lime reached 600 kPa, both showing rapid early gains. Nano-silica and Terrasil also improved strength, though at lower levels, and nano-carbonite compounds provided only marginal benefits (<150 kPa). Most improvement occurs within the first 28 days, after which gains plateau, confirming nano-copper and nano-alumina as the most effective stabilizers, producing UCS values 5–6 times higher than untreated soils.

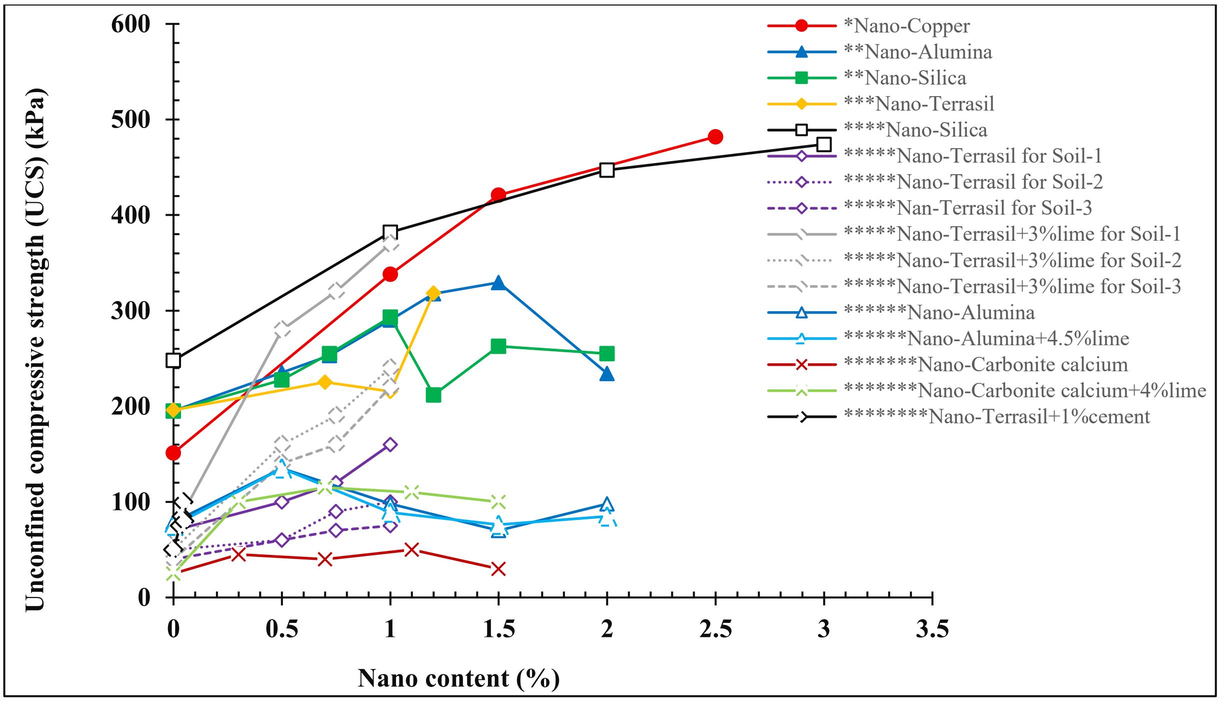

Figure 6. Effect of nanomaterials on unconfined compressive strength (UCS) of expansive soils
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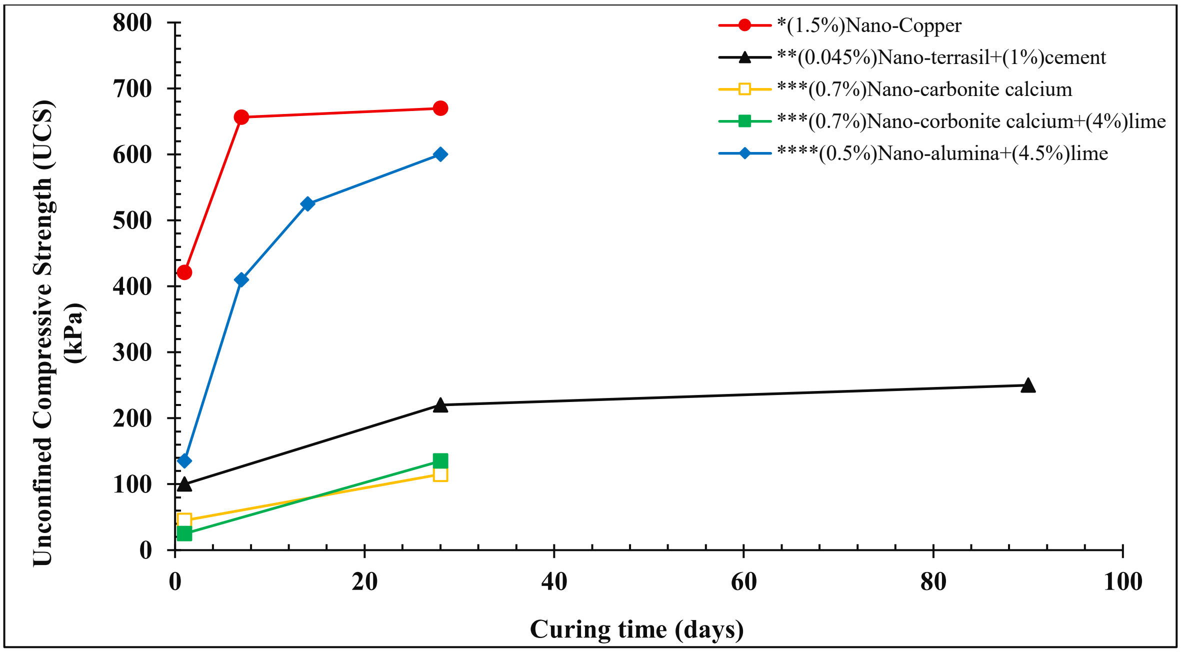

Figure 7. Effect of curing time on unconfined compressive strength (UCS) of expansive soils treated with different nanomaterials at optimum additive content
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4.2.2. California Bearing Ratio (CBR)

A collective data of CBR for expansive soils treated with nanomaterials focusing on soaked condition were plotted in Figure 8 to illustrate the effectiveness of various nano-additives: including nano-copper, Terrasil , MgO), nano-calcined clay, and nano-lime on CBR values. For instance, Pusadkar et al. [34] used nano-copper powder to stabilize expansive soils. It was found that just a 1.5% dose of nano-copper improve the soil's load-bearing strength by 116% compared to untreated soil. CBR improvements occur via several mechanisms, depending on the nanomaterial: nano-alumina, accelerates early-age strength development by reacting with soil minerals and forming bonding gels, contributing to higher CBR. Further, Mosa et al. [40] studied the stabilization of expansive subgrade soils using MgO at incremental dosages (0.1–1.5%). Specimens were prepared per standardized at optimal moisture content, sealed for 28-day curing to facilitate reactive processes, and subsequently soaked for 4 days to simulate moisture exposure. The CBR exhibited a dose-dependent response, escalating from 7.2% (0.1% MgO) to a peak of 36.0% at 0.7% MgO, a tenfold increase over untreated soil. Beyond this threshold, CBR values declined progressively to 19.5% at 1.5% MgO. This parabolic trend suggests dual competing mechanisms: at ≤0.7%, MgO enhances soil stability through pozzolanic cementation and particle aggregation. Promotes pozzolanic reactions forming CSH and CAH gels that cement clay particles, thereby increasing load-bearing capacity.

On the other hand, Pokkunuri et al. [38] investigated the stabilization of three expansive soil types using nano-Terrasil alone and, its combination with lime at 3%. Results showed that the CBR values under soaked conditions (4 days) without additives were 4.5%, 3.3%, and 1.86% for three different soil types. Nanomaterial incorporation significantly enhanced load-bearing capacity, with Terrasil yielding the significant CBR improvements. Further strength augmentation occurred with lime addition: 3% lime increased CBR values 5–6 times compared to nanomaterial-treated samples alone. The synergistic effect of nanomaterials and lime highlights their complementary stabilization mechanisms nanomaterials likely reduced porosity and water affinity, while lime induced pozzolanic cementation. The optimal stabilization of combines 1% Terrasil with 3% lime, achieving a 5-6 times CBR increase, which demonstrates the critical role of hybrid nanomaterial-lime treatments in transforming expansive soils into durable engineering substrates for moisture-prone environments. Further, Al-Swaidani et al. [37] examined the effect of a combination of nano-calcined clay and nano-lime, and the results were that adding just 2% nano-calcined clay improved soil strength significantly, but the extra change happened when they paired it with 0.6% nano-lime. Together, these nanomaterials worked in a way that nano-calcined clay filled microscopic gaps and reduced water sensitivity, while nano-lime acted as a binding agent, creating a tougher, more stable soil structure. The data showed this combination outperformed either material alone, proving that sometimes two solutions are better than one.

A review of CBR data for expansive soils treated with various nanomaterials (Figure 8) demonstrates substantial improvements in load-bearing capacity, with effects strongly dependent on nanomaterial type and dosage. Nano-copper at 1.5% increased CBR by 116% compared to untreated soil, reflecting its ability to enhance soil cohesion and particle bonding. MgO exhibited a dose-dependent response, with CBR rising from 7.2% at 0.1% to a peak of 36.0% at 0.7% a ten-time increase before declining to 19.5% at 1.5%, illustrating an optimal threshold for pozzolanic and aggregation effects. Terrasil, both alone and combined with 3% lime, markedly improved soaked CBR values across three expansive soils, with the hybrid treatment achieving a 5–6-time increase over nanomaterial-only samples, highlighting complementary mechanisms of reduced porosity and enhanced pozzolanic cementation. Similarly, combining 2% nano-calcined clay with 0.6% nano-lime yielded greater CBR gains than either additive alone, as the clay filled micro-voids while nano-lime bonded particles to create a more stable matrix. Collectively, these studies confirm that targeted nanomaterial treatments, particularly in combination with lime or complementary additives, can dramatically increase the load-bearing performance of expansive soils.

5. EFFECT OF NANOMATERIALS ON MICROSTRUCTURE OF EXPANSIVE SOILS

After adding nanomaterials to expansive soils, soil structures may alter accordingly as illustrated in Figures 9. To capture such changes, microscopic tests are usually conducted. For instance, Mosa et al. [40] found by conducting the Energy Dispersive X-Ray Analysis (EDX) that the MgO reacted with water to form magnesium hydroxide, which then teamed up with silica already in the soil to create a powerful glue-like binder called magnesium silicate hydrate (MSH). This MSH acts like nature's cement, locking soil particles together and making the ground stronger and more stable. The formation of MSH through MgO-silica reactivity demonstrates a dual chemical stabilization mechanism: pozzolanic cementation and particle bonding that effectively reinforces expansive soils, providing a robust foundation for geotechnical applications requiring long-term structural stability [46]. In addition, Al-Swaidani et al. [37] conducted a microstructural examination via SEM Scanning electron microscopy /EDX exhibited that untreated expansive soil presents a fragmented and loosely bound arrangement, notably lacking any hydration products. by using nano-calcined clay initiated a profound restructuring within the soil matrix, evidenced by the formation of calcium aluminosilicate hydrate (CASH) and calcium silicate hydrate (CSH) phases as illustrated in Figure 9. These cementitious materials establish an interconnected network that effectively binds the soil particles together, thereby enhancing its mechanical behaviour. Further, Shang and Fu [42] performed a SEM image for untreated expansive and they found that soil looks like a loose, crumbly mess full of gaps just waiting to swell with water. But add nano-alumina, cause soil transforms into a dense, gel-like network where particles clump together in tight clusters.

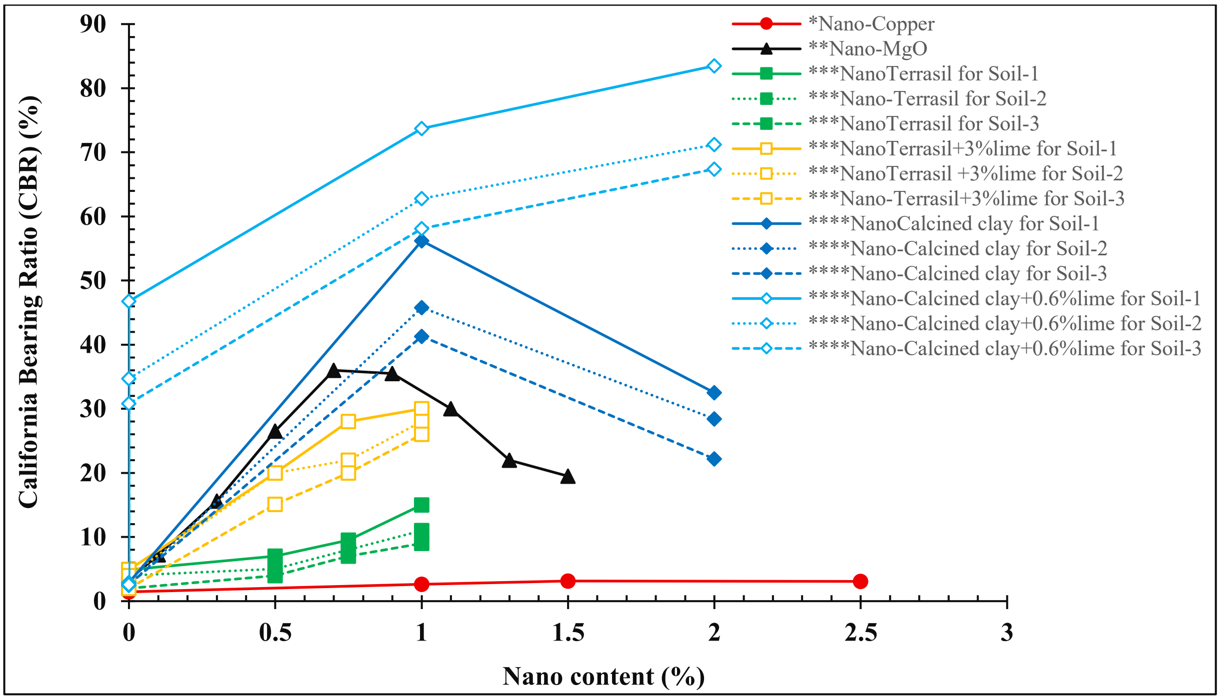

Figure 8. Effect of nanomaterials on California bearing ratio (CBR) of expansive soils.
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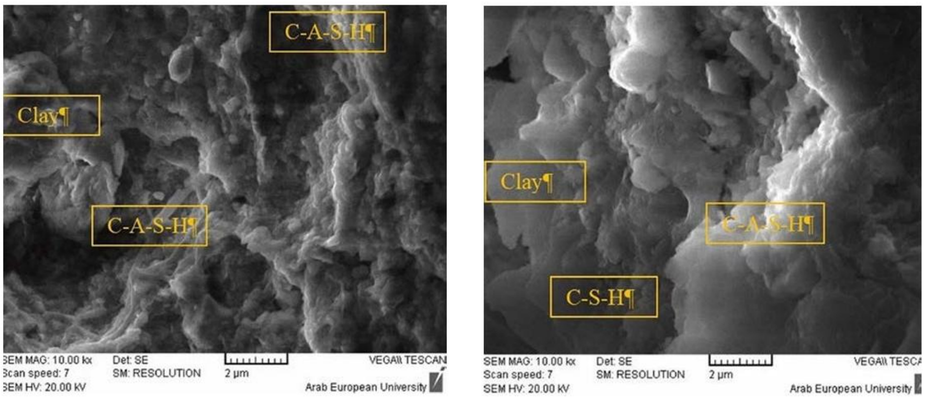
This new structure isn't just visually different, it's functionally tougher, like turning a pile of sand into reinforced concrete at the microscopic level. The nano-alumina acts like both a filler (plugging those problematic gaps) and a binder (creating chemical handshakes between soil particles). Furthermore, Awadalseed et al. [47] conducted a SEM analysis to see visually the densification of the soil matrix following nano-silica incorporation, attributable to the material’s high specific surface area, which have bonding with cement hydration products such as calcium silicate hydrate (CSH) and nano-silica gel [48]. These interactions establish a novel three-dimensional framework that interlocks with the inherent cementitious network, enhancing load distribution and reducing pore connectivity, and soil permeability [49]. The synergistic integration of nano-silica within the cement-modified soil not only amplifies mechanical resilience but also fortifies long-term durability by mitigating crack propagation and chemical degradation pathways. Moreover, Abdelrahman et al. [39] performed SEM and the observations showed that the combination of nano-silica and nano-metakaolin performs a dual role in soil stabilization. These nanomaterials permeate the pore structure of the soil, acting as void fill and bridging microcracks, ultimately reducing pore space to a large extent. The more homogeneous dispersion shows better spreading between clay and newly formed cementitious phases that ultimately leads to a strong interfacial bond. It is worth mentioning that nano-silica serves by generating siloxane links, while nano-metakaolin activates pozzolanic reactions leading to the development of CSH gels. Collectively, these processes result in changed soil structure promoting a greater load-bearing capacity, reduced hydraulic conductivity, and higher swelling resistance. In related study Bahmani et al. [50] performed microstructural analysis via SEM to see the cement-nano silica composites induce a densely in soil matrix with reduced pore connectivity, causing interaction between cement hydration products and alumina nanoparticles. The observed structural densification from two concurrent mechanisms: Pozzolanic reactivity between nano-silica and cement phases generates secondary calcium silicate hydrate (CSH) gels that encapsulate soil particles, enhancing interfacial adhesion, and nanoscale alumina particles occupy intergranular voids. This dual-phase reinforcement chemical bonding via CSH formation and physical pore-filling creates a cohesive microstructure resistant to deformation and moisture ingress. Using microstructural analysis via SEM and X-ray diffractions, Pachideh et al. [51] reported that treating expansive soils with lime-nano silica less susceptible to temperature comparing with adding lime alone due to greater number of additive's particles and faster process of pozzolanic reactions. However, applying of lime-nano silica in cold region and short time intensified the lime effect.

Nanomaterials profoundly alter the microstructure of expansive soils, enhancing particle bonding, densification, and overall mechanical performance. Microstructural analyses (SEM and EDX) consistently show that untreated soils are loosely bound with high porosity, while incorporation of nanomaterials generates cementitious gels and fills voids [52]. For example, MgO reacts with silica to form magnesium silicate hydrate (MSH), acting as a dual stabilizer through pozzolanic cementation and particle bonding, while nano-calcined clay produces calcium aluminosilicate hydrate (CASH) and calcium silicate hydrate (CSH) networks that interconnect soil particles. Nano-alumina and nano-silica create dense, gel-like frameworks, with nano-alumina filling gaps and forming chemical bonds, and nano-silica interacting with cement hydration products to generate a three-dimensional network that reduces pore connectivity and strengthens interfacial adhesion. Combinations such as nano-silica with nano-metakaolin further enhance stabilization by bridging microcracks, filling pores, and promoting CSH formation. Collectively, these nanomaterial-induced microstructural changes lead to higher load-bearing capacity, reduced hydraulic conductivity, improved swelling resistance, and long-term durability of expansive soils.



(a) (b)

Figure 9. SEM for a. nana-calcined clay and b nano-calcinedclay+0.6%nano-lime (After [37]).

6. CONCLUSIONS

This review highlights the transformative role of nanomaterials in mitigating the adverse geotechnical behaviour of expansive soils. The following conclusion can be drawn:

1. Nanomaterials lower PI by 20–60% (from 30–40% to less than 20–25% at ≤1% nanomaterial), while hybrids (e.g., 2% nano-calcined clay + 0.6% lime) reduce PI to 5–8%, confirming strong synergy.
2. Less than 1% Nanomaterials can reduce OMC and raise MDD by 10-12%**.** Hybrid stabilization optimize densification with OMC reduction to 10–15% and MDD increases to 5-7%.
3. For short-term curing, swell potential falls by 30–70% and swell pressure reduces by 20-30% for nanomaterials and even more reduction with hybrid stabilization, while for long-term curing even more enhancement was reported especially at 28 days.
4. Short-term UCS improvements reach to 90% and to more than double in comparsion to untreated soil for long-term curing. Interestingly, USC can reach to 5 to 6 times the untreated soil for long term (28 days) under hybrid stabilization.
5. Soaked CBR doubles with nanomaterials, and rises to 5–6 times with hybrid stabilization.
6. SEM analysis shows that nanomaterials densify soil, fill voids, and form cementitious gels (CSH,

CAH, MSH, CASH), improving bonding, reducing porosity, and enhancing strength, stability, and load-bearing capacity. Hybrid nanomaterials further reinforce the soil by bridging microcracks and strengthening bonding.
7. Low dosages (≤1–1.5%) deliver high performance with reduced environmental impact versus cement/lime, making nanomaterials a cost-effective, sustainable stabilization strategy.

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