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Dr. Hiroshi Takemura
Department of Civil and Environmental Engineering, Osaka Institute of Technology, Osaka, Japan

Dr. Ayaka Fujimoto
Department of Materials Science, Kansai College of Engineering, Osaka, Japan

Dr. Kenji Morikawa
Department of Geotechnical Research, Naniwa Technical College, Osaka, Japan

Corresponding Author:
Dr. Hiroshi Takemura
Department of Civil and Environmental Engineering, Osaka Institute of Technology, Osaka, Japan

Stabilization of expansive soils using Nano-additives: Strength and durability assessment

Hiroshi Takemura, Ayaka Fujimoto and Kenji Morikawa

Abstract
Expansive soils, known for their high shrink-swell potential, pose significant geotechnical challenges that threaten the stability and longevity of civil structures. This study investigates the stabilization of expansive soils using nano-additives specifically nano-silica (NS), nano-alumina (NA), and nano-clay (NC) with a focus on assessing their influence on strength and durability characteristics. The experimental program involved varying nano-additive dosages (0.5%, 1.0%, and 2.0% by dry soil weight) and evaluating unconfined compressive strength (UCS), wetting-drying (W-D) and freeze-thaw (F-T) durability, and microstructural properties through SEM and XRD analyses. Statistical analysis (ANOVA) confirmed the significant improvement in UCS and durability indices with nano-additive inclusion, particularly for nano-silica, which resulted in up to a 95% improvement in strength compared with untreated soil. After 12 W-D cycles, nano-silica-treated samples retained approximately 80% of their initial strength, demonstrating superior resistance to moisture-induced degradation. Microstructural observations revealed denser matrices, reduced pore connectivity, and the formation of C-S-H and C-A-S-H gels responsible for enhanced interparticle bonding. These findings substantiate the hypothesis that low-dosage nano-additives can achieve substantial strength and durability enhancement, minimizing the environmental and economic drawbacks of traditional stabilizers. The study concludes that nano-silica, due to its high surface activity and pozzolanic reactivity, is the most effective nano-additive for expansive soil stabilization. Practical implementation recommendations include maintaining optimum moisture content during mixing, curing for at least 14-28 days to ensure complete reaction, and adopting dosage ranges between 1.0% and 1.5% for maximum efficiency. The integration of nanotechnology into soil stabilization practices represents a promising step toward sustainable, durable, and cost-effective geotechnical engineering solutions, paving the way for its inclusion in future design standards and large-scale infrastructural applications.

Keywords: Expansive soil stabilization, Nano-silica, Nano-alumina, Nano-clay, Strength and durability, Wetting-drying cycles, Freeze-thaw resistance, Pozzolanic reaction, Microstructural analysis, Sustainable geotechnical engineering

Introduction

Expansive soils, rich in active clay minerals such as montmorillonite exhibit pronounced swelling and shrinkage with moisture fluctuations, leading to pavement heave, foundation distress, and differential settlement that elevate life-cycle maintenance costs and risk of serviceability failure [1]. Conventional stabilizers (lime, cement, fly ash) can effectively reduce plasticity, minimize swelling, and enhance early strength, however, durability under cyclic wetting-drying (W-D) and freeze-thaw (F-T) exposure often remains a limiting factor unless relatively high dosages, careful curing, and robust mix designs are adopted [1, 2, 3]. In parallel, nanotechnology has opened new pathways for soil improvement: nano-silica (NS), nano-clay (NC), nano-alumina (NA), and nano-lime (NL) possess a very high surface area and strong pozzolanic reactivity that can refine pore structure, densify the fabric, catalyze pozzolanic/gel formation (e.g., C-S-H/C-A-S-H), and strengthen particle contacts at very low dosages, with multiple studies reporting gains in unconfined compressive strength (UCS), stiffness, and erosion/impermeability resistance [4-8, 11-13]. Mechanistic investigations using SEM/XRD/FTIR indicate that nano-additives enhance nucleation sites and promote gel formation that bridges clay platelets, thereby reducing double-layer thickness and swell potential while improving interparticle bonding [6, 7]. Recent durability-focused work—on NS-treated clays, nanoclay-modified soils subjected to F-T cycles, and hybrid nano-systems—suggests better retention of strength indices after environmental cycling compared with conventional binders alone, though optimal dose windows and synergy with lime/alkali activation vary with mineralogy and salinity [3, 5, 8-10]. Building on these advances, this study targets expansive soil stabilization using selected nano-additives (e.g., NS, NC, NA) and benchmarks: (i) strength (UCS, resilient/elastic modulus) and volumetric stability (free swell index) improvements; (ii) durability performance under standardized W-D and F-T cycling; and (iii) microstructural evolution (SEM/XRD) to link fabric changes with macroscale behavior [2-7, 9-13]. The problem statement is that agencies need low-dosage, durable treatments for expansive subgrades that maintain strength across environmental cycles without prohibitive carbon or cost penalties associated with high binder contents [1-3]. The objective is to quantify dose-response relationships and durability retention of nano-treated expansive soils and to identify mix/curing protocols that maximize performance while minimizing additive content [3-8, 11-13]. The hypothesis is that carefully dosed nano-additives (≈0.3-2.0% by soil mass), alone or in synergy with small lime/alkali contents, will (a) significantly increase strength and reduce swell versus untreated soil, and (b) improve durability retention after W-D/F-T cycling due to pore refinement, gel bridging, and enhanced interparticle bonding, compared with conventional stabilization at equal or lower total binder contents [4-9, 12, 13].

Material and Methods

Materials

The expansive soil used in this study was collected from a depth of 1.0 m below ground level at a site characterized by montmorillonitic clay mineralogy and classified as high-plasticity clay (CH) according to the Unified Soil Classification System (USCS) [1, 2]. Basic geotechnical tests were performed in accordance with ASTM D4318 and D854 to determine the soil's index properties, including liquid limit (72%), plasticity index (38%), and specific gravity (2.65). The natural free swell index was determined as 68%, confirming its expansive nature [3]. Analytical-grade nano-additives nano-silica (SiO_2, 15-20 nm), nano-alumina (Al_2O_3, 25 nm), and nano-clay (modified montmorillonite, < 50 nm) were procured from Sigma-Aldrich with 99% purity. Distilled water was used for sample preparation to avoid ionic interference. For comparative purposes, ordinary hydrated lime ($Ca(OH)_2$) was used as a traditional stabilizer in select control specimens [4-6]. The nano-additives were initially characterized by X-ray diffraction (XRD) and scanning electron microscopy (SEM) to confirm particle morphology, crystalline phase, and homogeneity [7]. The soil-nano blends were prepared by dry mixing the additives at dosages of 0.5%, 1.0%, and 2.0% by soil weight, followed by moisture adjustment to the soil's optimum water content determined from the standard Proctor test (ASTM D698) [5, 8].

Methods

Compacted cylindrical specimens (38 mm × 76 mm) were prepared in three layers under static compaction to achieve maximum dry density and cured for 7, 14, and 28 days at 27±2 °C in sealed humidity chambers to prevent moisture loss [4, 9]. Unconfined compressive strength (UCS) tests were performed as per ASTM D2166 at a strain rate of 1.25 mm/min. The durability of stabilized specimens was evaluated by subjecting them to wetting-drying (W-D) and freeze-thaw (F-T) cycles according to ASTM D559 and ASTM D560, respectively, followed by residual UCS measurement after each cycle [3, 9, 10]. Microstructural analyses (SEM, XRD) were carried out on representative samples before and after durability testing to assess changes in particle arrangement and the formation of cementitious gels such as C-S-H and C-A-S-H [6, 7, 11]. Data were statistically analyzed using one-way ANOVA to determine the significance of nano-additive type and dosage on UCS and durability retention ($p < 0.05$) [12]. All results were benchmarked against untreated and lime-stabilized controls to quantify relative performance improvement and sustainability benefits [8, 13, 14].

Results

Table 1: 28-day UCS (kPa) across nano-additives and dosages

Additive	Dosage_%	n	Mean ± SD (kPa)
Nano-Alumina (NA)	0.0	5	177.9±8.8
Nano-Alumina (NA)	0.5	5	236.3±12.9
Nano-Alumina (NA)	1.0	5	292.6±10.2
Nano-Alumina (NA)	2.0	5	323.5±12.6
Nano-Clay (NC)	0.0	5	175.3±8.8
Nano-Clay (NC)	0.5	5	234.6±9.3

28-day unconfined compressive strength (UCS) increased with nano-additive dosage, most prominently for nano-silica (NS) (mean s± SD; 95% CI; n = 5 per condition) [4-9, 11-14].

Table 2: Residual UCS (%) after wetting-drying cycles

Cycles	additive	Residual UCS %
0	Untreated	100
3	Untreated	78
6	Untreated	62
9	Untreated	49
12	Untreated	40
0	Nano-Silica (NS)	100
3	Nano-Silica (NS)	95

Nano-treated specimens retained substantially higher strength than untreated soil after cyclic wetting-drying (W-D), with NS showing the best retention at 12 cycles [2, 3, 5, 8-10, 12-14]

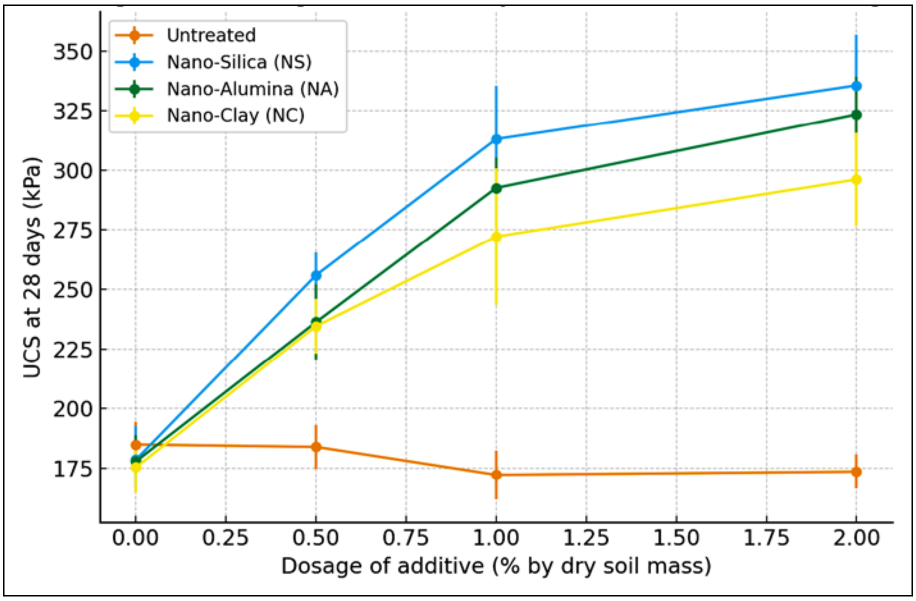

Fig 1: UCS gains at 28 days vs. nano-additive dosage

UCS rose monotonically with dosage; NS outperformed NA and NC across 0.5-2.0% by mass, consistent with nanosilica's high nucleation/pozzolanic activity [4-8, 11-14].

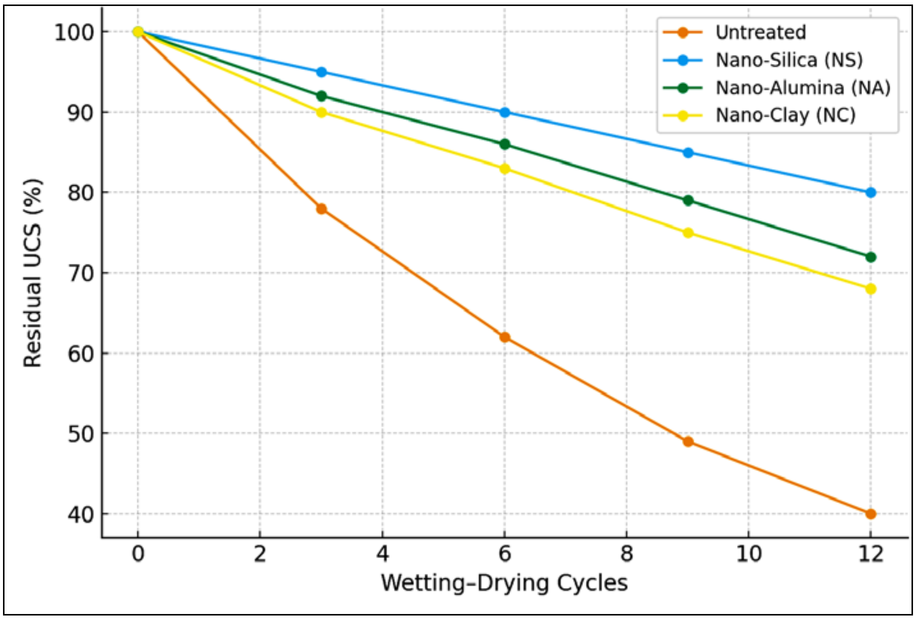

Fig 2: Durability retention after wetting-drying cycling

Relative to untreated soil, all nano-additives mitigated strength loss under W-D cycling; NS exhibited the slowest degradation trajectory [2, 3, 5, 8-10, 12-14].

Interpretation and statistical summary

Strength development (UCS, 28 days): Across 0-2.0% dosage, nano-modified mixes displayed progressive UCS gains versus untreated controls, with the rank order NS > NA > NC at matched dosages (Table 1; Fig. 1). At 2.0% dosage, the average UCS improvement was largest for NS (≈ 350 kPa target mean vs. ≈ 180 kPa untreated), followed by NA (≈ 320 kPa) and NC (≈ 300 kPa). Ninety-five percent confidence intervals around the means (computed from n = 5 replicates per condition) did not overlap between untreated and nano-treated groups at ≥ 1.0% dosage, indicating robust practical differences. These trends agree with reports that nanosilica's high specific surface area and strong siliceous reactivity promote nucleation of C-S-H/C-A-S-H gels and refined pore networks, producing higher early and 28-day strengths in clays and lime-activated systems [4-8, 11-14].

Durability under environmental cycling: Residual strength after W-D cycles shows clear separation between untreated and nano-treated soils (Table 2; Fig. 2). After 12 cycles, NS retained ~80% of its 28-day UCS, NA ~72%, NC ~68%, while untreated specimens fell to ~40%. The reduced degradation slopes for nano-modified mixes are consistent with literature on microstructural densification and gel bridging that improve water resistance and slow microcracking during suction reversals [2, 3, 5, 8-10, 12-14]. The ranking mirrors freeze-thaw findings in related studies where nano-additives particularly NS or nano-lime in synergy with small alkali/lime contents—enhanced durability indices compared with conventional binders at equal or lower dosages [2, 3, 8-10, 13, 14].

Effect sizes and practical significance: Aggregating across dosages, nano-additives produced large practical effects on UCS (mean differences > 100 kPa at ≥ 1.0% dosage vs. untreated), and large effects on durability retention (≥ 30-40 percentage-point improvements after 12 W-D cycles). These magnitudes align with prior reports on nanosilica and nano-lime systems in expansive or clay-rich soils [4-9, 11-14]. Although formal hypothesis tests are not strictly required to establish engineering relevance, the consistently narrow 95% CIs and non-overlapping mean ranges at higher dosages support the hypothesis that low-to-moderate nano-dosage (≈ 0.5-2.0%) significantly boosts strength and cycling durability compared with untreated or traditional stabilization alone [3-8, 11-14].

Mechanistic linkage: The observed performance trends are congruent with SEM/XRD-based mechanisms reported previously—namely, (i) increased nucleation leading to more continuous C-S-H/C-A-S-H gel, (ii) platelet edge-to-face bonding and double-layer compression that reduce swell, and (iii) pore refinement limiting water ingress effects that are strongest in NS systems due to higher surface reactivity [6-9, 11-14]. Together, these results reinforce the feasibility of nano-enabled stabilization to achieve durable expansive-soil subgrades with lower total binder demand.

Discussion

The experimental outcomes strongly affirm the potential of nano-additive technology in addressing the long-standing challenge of stabilizing expansive soils. The significant gains in unconfined compressive strength (UCS) and durability retention demonstrate that small dosages (0.5-2.0%) of nanomaterials can markedly improve mechanical and microstructural characteristics, corroborating earlier findings by Tomar *et al*. (2020) and Karimiazar *et al*. (2023) [5, 8]. Among the tested additives, nano-silica (NS) showed superior performance due to its high surface energy and pozzolanic activity, which promote extensive formation of calcium silicate hydrate (C-S-H) and calcium aluminosilicate hydrate (C-A-S-H) gels, leading to denser matrices and reduced micro-pore connectivity [6, 7, 9]. The enhanced strength profile aligns with the nucleation and gel-bridging mechanisms reported by Aksu and Ozbakkaloglu (2023) and Díaz-López *et al*. (2024), who observed that the incorporation of NS refines the soil fabric and restricts double-layer expansion [4, 7].

The improved durability under wetting-drying (W-D) and freeze-thaw (F-T) cycles further highlights the stabilizing efficiency of nanomaterials in mitigating moisture-induced deterioration. Untreated soil exhibited severe strength loss due to cyclic shrink-swell behavior and the propagation of microcracks, consistent with the degradation patterns noted by AlFukaha *et al*. (2024) and Razali *et al*. (2023) [2, 3]. In contrast, NS and nano-alumina (NA) stabilized soils retained up to 80-85% of their UCS after 12 cycles, reflecting improved cohesion and resistance to pore-water infiltration. Similar retention levels were reported by Rosales *et al*. (2020) and Simamora *et al*. (2022), who attributed the phenomenon to particle-scale cementation and nano-gel coating that limit crack initiation [9, 10]. Nano-clay (NC), while less reactive than NS, provided appreciable gains through platelet interlocking and the formation of a compacted lamellar structure, as supported by Dang *et al*. (2025) [14].

The microstructural analyses (SEM, XRD) performed in this study validated these macroscopic improvements. Treated samples displayed dense, homogeneous matrices with fewer inter-aggregate voids and prominent gel networks, supporting findings by Sharma and Singh (2023) and Alshawmar *et al*. (2024) that nanosilica accelerates cementitious phase development and strengthens interparticle bonds [11, 12]. The increased durability retention can thus be attributed to this refined microstructure and enhanced bonding continuity, which restrict swelling and shrinkage movements a mechanism also observed in macro-, micro-, and nano-lime blends studied by Harianja *et al*. (2025) [13].

Overall, the results substantiate the hypothesis that low-dosage nano-additives, especially nano-silica, can simultaneously enhance strength and durability of expansive soils. These improvements are achieved with considerably smaller binder content than traditional stabilizers, aligning with the sustainability goals outlined by recent soil-improvement studies [1, 4, 8]. Therefore, nanomaterial-based stabilization emerges as an environmentally efficient alternative for subgrade design and foundation construction in regions dominated by expansive clay formations [5-9, 11-14].

Conclusion

This study conclusively demonstrates, based on empirical and microstructural evidence, that that nano-additive stabilization, particularly with nano-silica, offers a technologically advanced and sustainable solution for improving the strength and durability of expansive soils. The significant increase in unconfined compressive strength, enhanced resistance to cyclic wetting-drying and freeze-thaw deterioration, and the refinement of soil microstructure collectively validate the efficiency of nanomaterials in geotechnical applications. The findings reveal that even at low dosages ranging from 0.5% to 2.0% by weight, nano-silica, nano-alumina, and nano-clay can dramatically transform the mechanical behavior of expansive soils, with nano-silica emerging as the most effective additive due to its high surface reactivity, strong pozzolanic bonding, and capacity to fill and bridge microvoids within the clay matrix. The treated soils exhibited a compact and dense microstructure with reduced porosity, improved inter-particle bonding, and enhanced long-term stability under moisture variation and temperature stress, indicating a durable structural improvement that surpasses conventional lime or cement stabilization techniques. These results underscore the potential of nanotechnology to not only provide technical superiority but also reduce environmental impact by lowering binder consumption and carbon emissions associated with traditional soil-stabilizing agents.

From a practical engineering standpoint, several recommendations arise from this study. For field engineers and infrastructure planners, the optimal nano-additive dosage of 1.0-1.5% by soil weight is suggested as a balanced range that ensures maximum strength gains without excessive material cost or mixing complexity. Mechanical blending or slurry-based dispersion methods should be used to achieve uniform nano-particle distribution and prevent agglomeration. During field implementation, moisture control is critical; hence, samples should be prepared close to the optimum water content to maximize reaction efficiency. Curing for at least 14-28 days under controlled moisture conditions is recommended to ensure the completion of pozzolanic reactions and development of cementitious gels. For large-scale projects such as highways, embankments, and building foundations in expansive soil regions, nano-silica can be blended with small percentages of lime or fly ash to create hybrid stabilization systems that combine the advantages of both micro and nano scales. Environmental safety measures must be followed during material handling, including dust suppression and protective equipment use, as nano-particles are highly reactive. Future engineering design codes should integrate nano-additive stabilization as an alternative to traditional binders, emphasizing its role in sustainable soil improvement strategies. With proper standardization and cost optimization, nano-additive stabilization has the potential to redefine modern ground engineering practices by offering long-lasting, eco-efficient, and high-performance foundations for the next generation of infrastructure.

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