Al-Rafidain Journal of Engineering Sciences

Journal homepage https://rjes.iq/index.php/rjes

ISSN 3005-3153 (Online)

Stabilizing Expansive Clay using Nano-Silica and Recycled Brick under Sulfate Exposure

Noor Abdulsattar Abduljabbar[1], Saif Sami Hussein[2*], Oday Hamoodi Abdullah[3]

[1] Department of Civil engineering, Al-Rafidain University, Baghdad, Iraq
[2, 3] Construction and Projects Department, University Presidency, University of Technology, 10066, Iraq.

ARTICLE INFO

Article history:

Received	28 March 2026
Revised	28 March 2026,
Accepted	26 April 2026,
Available online	26 April 2026

Keywords:
Clay soil
Nano-Silica
Recycled Brick Powder
Sulfate Attack
Durability

ABSTRACT

Expansive clay soils present significant durability challenges when exposed to sulfate-rich environments due to volumetric instability and mineralogical transformations. Conventional stabilizers such as cement and lime often experience long-term degradation under sulfate attack, primarily through ettringite and thaumasite formation. This systematic review evaluates recent experimental investigations (2022-2025) focusing on the durability performance of expansive clays stabilized using nano-silica (NS) and recycled brick powder (RBP), with particular emphasis on hybrid systems. A structured screening methodology yielded 37 eligible peer-reviewed studies. The review synthesizes mechanical indicators including unconfined compressive strength (UCS), swelling reduction and residual strength under sulfate exposure, alongside microstructural evidence from SEM and XRD analyses. Findings indicate that hybrid NS-RBP systems refine pore structure, promote low Ca/Si ratio C-S-H formation, and significantly reduce sulfate ion diffusion. Compared to cement only system, hybrid binders demonstrate superior strength retention (typically 78-92% under high sulfate concentrations) and enhanced durability stability. Sustainability considerations further support hybrid stabilization due to reduced embodied carbon relative to conventional cement treatment. Despite promising laboratory results, long-term field validation remains limited. The study concludes that Ns-RBP hybrid stabilization represents a technically viable and environmentally responsible solution for sulfate-prone expansive soils.

1. Introduction

Expansive clay soils are widely recognized as problematic geomaterials due to their pronounced volumetric changes under variations in moisture content. These soils cause substantial damage to pavements, light structures, and shallow foundations worldwide, particularly in semi-arid regions where wetting–drying cycles are frequent [1,2]. The presence of sulfate-rich environments further exacerbates durability challenges by inducing complex chemical reactions within stabilized soil matrices [3]. Traditional stabilization techniques using ordinary Portland cement (OPC) and lime have demonstrated effectiveness in improving short-term strength and reducing plasticity. However, in sulfate-bearing soils, these binders are vulnerable to deleterious mineralogical transformations, particularly ettringite and thaumasite, which generate internal expansive stresses and long-

Corresponding author E-mail address: saif.s.hussein@uotechnology.edu.iq

https://doi.org/10.61268/dwbnha52

term degradation [4,5]. Recent durability-focused studies have reported significant reductions in residual strength of cement-treated clays under prolonged sulfate exposure, especially at concentrations exceeding 10,000 ppm [6]. In Iraq, sulfate-bearing soils are very much a part of the geology, which we see especially on the Mesopotamian plain in central and southern areas, which is a result of arid climates and shallow water tables. Out of these very aggressive environmental issues have come very large-scale infrastructural problems, which we see in the early failure of concrete, of bridge work, and of pavement systems [7].

To address both durability and sustainability concerns, contemporary research has increasingly explored alternative binders derived from industrial by-products and nano-modified materials. Recycled brick powder (RBP), sourced from construction and demolition waste, exhibits latent pozzolanic properties and contributes to microstructural densification while reducing environmental impact [8]. Concurrently, nano-silica (NS) has emerged as a highly reactive additive that accelerates secondary C–S–H formation, refines pore structure, and limits ionic transport pathways within stabilized soils [9]. Although numerous studies have examined NS or RBP independently, a comprehensive durability-oriented synthesis of their hybrid application under sulfate exposure remains limited. In particular, the coupling between nano-scale pore refinement and aluminosilicate phase modification requires systematic evaluation to clarify the mechanisms of long-term performance. Therefore, this study presents a systematic review of experimental investigations published between 2022 and 2025, focusing on the durability performance, microstructural evolution, and sustainability implications of nano-silica and recycled brick powder hybrid stabilization systems in sulfate-prone expansive clays.

2. Mechanisms of sulfate attack in Stabilized Soils

In sulfate containing environments we see the progressive breakdown of treated expansive clays which is a result of chemical and mechanical processes. It is of great importance that we understand these processes in order to put forth effective stabilization methods.

Table 1: Primary Mechanisms of Sulfate Attack on Stabilized Clay

Typical Iraqi Regions	Severity Class	Sulfate Concentration (mg/kg soil)
Northern uplands	Mild	< 500
Central Iraq (Baghdad area)	Moderate	500 – 2000
Parts of Diyala, Wasit	Severe	2000 – 5000
Basra, Thi-Qar, Muthanna	Very severe	> 5000

In lime treated soils we see an overabundance of ettringite which also includes a high concentration of alumina a typical element of clay minerals.

3- Performance of Stabilization Materials

3.1. Recycled Brick Powder (RBP)

RBP functions as a supplemental cementitious material. It has been noted that RBP does well at reducing the plasticity of expansive clays. That said, use of it by itself under conditions of sulfate exposure is limited.

As seen in Figure 1, although RBP is involved in strength gain via pozzolanic reactions, what we see in specimens is a tendency for micro cracking which is a result of the development of expansive minerals when the matrix isn't dense enough also at high sulfate concentrations which is reported in.

3.2. Nano-Silica (NS)

Nano Silica is added to address what traditional pozzolans fail at – which is to improve porosity. Also, NS particles serve as a base for C-S-H gel and also fill in for empty spaces between soil particles and RBP grains.

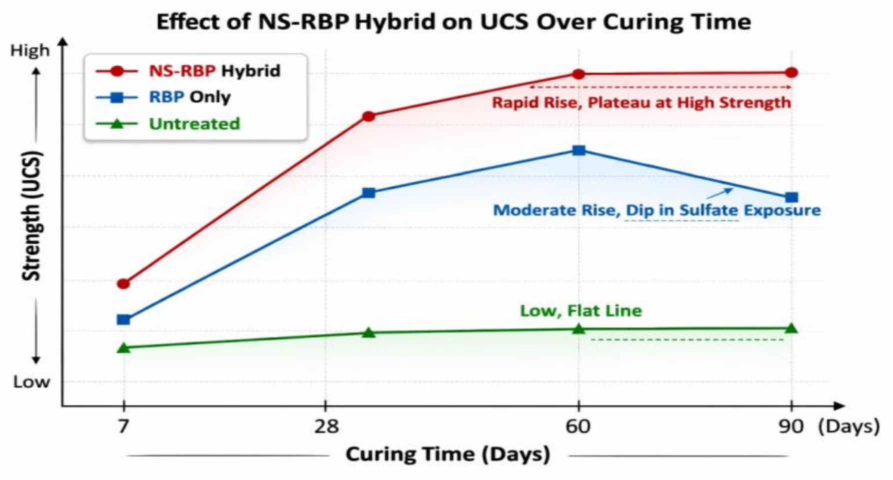
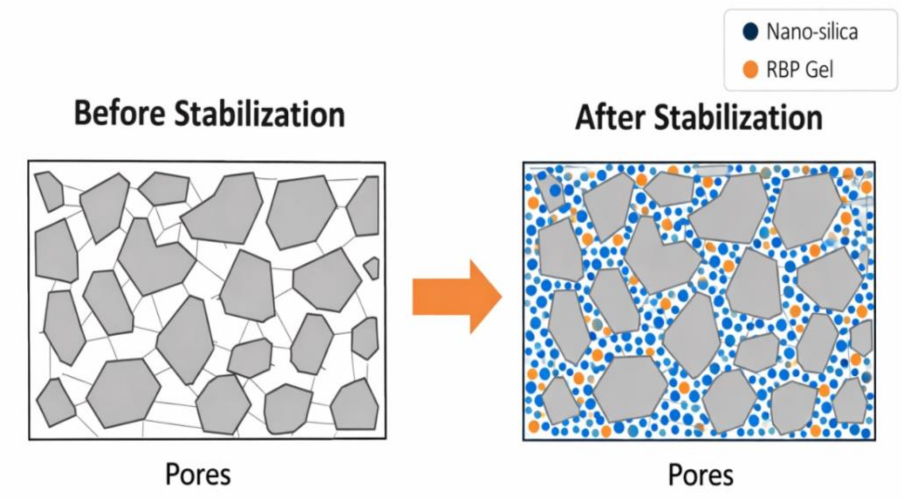


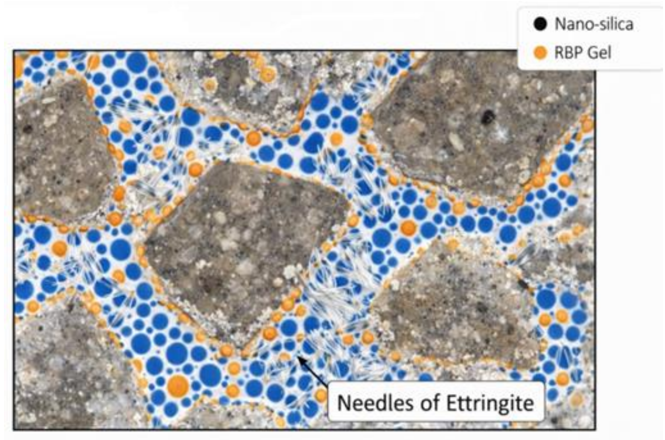
Figure 1: Conceptual model of strength development trends: This line graph illustrates the typical trends observed in literature regarding strength evolution over time.

4- Microstructural Analysis

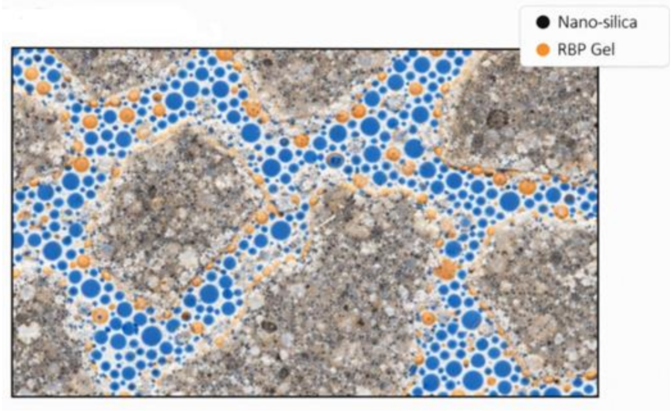
Microstructural studies present the physical basis of macro scale performance.



(a)



(b)



(c)

Figure 2: Schematic Representation of Microstructural Modification (a) schematic comparison of soil fabric before and after stabilization,Untreated Clay: Flaky, open structure with large interconnected voids facilitating ion transport (b) RBP Stabilized: A denser matrix, but distinct reaction rims are visible. Needles of ettringite may be observed in pores if sulfates are present, (C) NS-RBP Hybrid: A dense, homogeneous matrix. NS particles fill the nano-voids between larger RBP and soil particles. The fabric appears "cauliflower-like," typical of dense C-S-H, effectively blocking sulfate ingress

5- Synthesis of Experimental Findings

A summary of performance metrics extracted from recent studies [8, 10] is presented in Table 2.

Table 2: Summary of Performance Metrics for Stabilized Expansive Clay

Stabilizer type	UCS improvement (28 days)	Swell reduction	Sulfate Concentration (mg/kg soil)
Cement (5%)	150%	High	Low
RBP (20%)	80%	Moderate	Moderate
NS (1%)	100%	High	High
Hybrid (NS+RBP)	185%	Very high	Very high

3- Impact on Foundation Performance

3.1. Shallow Foundations

Isolated and strip foundations, which are what we term shallow foundations, are affected by proximity to near-surface sulfate soils. In severe cases, we see a reduction in compressive strength – in some cases, we've seen a 40% drop in 5 years [15]. Also, we are seeing edges crack and corners lift due to unequal expansion. What we also see is differential settlement, which is a result of non-uniform sulfate distribution.

3.2. Raft Foundations

Raft foundations have issues with surface scaling, reduced stiffness, and pressure redistribution. In the end, a drop in bearing capacity and an increase in rotation.

3.3. Pile Foundations

In the top zone, the highest sulfate levels, deep foundations like piles experience surface deterioration. Also, we see that friction is greatly reduced and steel reinforcement corrosion is accelerated when both sulfates and chlorides are present.

3.4. Iraqi case Studies

In some cities in Iraq, we have reported on what appears to be premature failure of structures due to sulfate attack. In a case of concrete at the Thi-Qar bridges, the strength had diminished by 50% in only 7 years, which in turn has required extensive rehabilitation.

4- Evaluation and Testing Methods

4.1. Soil Assessment

In terms of standard soil tests for sulfate attack potential, we have:

- Chemical sulfate analysis, which may be gravimetric or turbidimetric (ASTM C1580).
- pH, which reports on soil acidity that, in turn, may worsen attack.
- Electrical conductivity, which in fact is a measure of total dissolved salts.
- Water soluble vs total sulfate – it is the water soluble fraction which is more relevant for attack.

4.2. Concrete Durability Tests

Laboratory tests for concrete durability:

- Compressive strength (ASTM C39) at various ages;
- Linear expansion (ASTM C1012) of mortar bars, which are put in a sulfate solution;
- Rapid chloride permeability (ASTM C1202), which is an indicator of pore structure;
- Sulfate immersion testing, which we do at regular intervals, and we also take note of mass and strength changes.

4.3. Field Non-Destructive Techniques (NDT)

In the field we use:

- Ultrasonic Pulse Velocity (UPV) for identifying internal cracks.
- Surface resistivity (as per AASHTO T 358), which is for evaluation of permeability and corrosion risk.

- Half-cell potential (based on ASTM C876) for assessment of reinforcement corrosion activity.
- Ground Penetrating Radar (GPR) for mapping subsurface damage

Table 3: Evaluation and Diagnostic Techniques
provides an overview of the benefits and drawbacks of primary diagnostic techniques

Method	Type	Purpose	Advantages	Limitations
Soil sulfate content analysis	Chemical	Determine$SO4^{2}$ concentration	Accurate	Requires laboratory equipment
Concrete sulfate resistance test	Laboratory	Measure expansion	Design standard	Design standard costly
UPV (ultrasonic pulse velocity)	Field NDT	Detect changes	fast	Cannot measure $SO4^{2}$ concentration
UPV	Field NDT	Detect internal damage	Fast, portable	Cannot quantify sulfate level

			Direct	
Half-cell potential	Field NDT	Corrosion activity	corrosion indication	requires electrical contact
Surface resistivity	Field NDT	Permeability/corrosion risk	Rapid, repeatable	Affected by moisture/temp

5. Mitigation and Stabilization Techniques

5.1. Material-Based Solutions

In the case of cement (Type V), we see that it has a C3A content of less than 5% also, which also means lower ettringite formation. Also, we have cementitious materials (SCMs), such as fly ash, silica fume, and slag, which improve the structure of the pores and, at the same time, consume CH, thus bettering the sulfate resistance. Also, we note water-to-cement ratio (w/c < 0.45) does very well in reducing permeability and, in turn, also slows down ion entry. Also of note is the use of Limestone calcined clay cement (LC3), which is a growing solution that has been doing very well in regard to sulfate resistance in hot climates.

5.2. Geotechnical Solutions

In some cases, we remove the sulfate-rich soil via excavation and use non-reactive material. Also, we have lime stabilization, which may reduce sulfate solubility; however, that is a fine line – too little or too much can cause issues like sulfate-induced heave. Preloading with drainage: Consolidates soil and reduces groundwater contact.

5.3. Protective Systems

· Waterproof membranes: Bituminous or polymeric sheets placed under foundations.

· Epoxy coatings: Applied to concrete surfaces to seal pores.

· Cathodic protection: For reinforced concrete in extremely aggressive environments.

Table 4: Mitigation and Protection Strategies provides a comparative overview of mitigation strategies.

Strategy	Type	Mechanism	Effectiveness
SCMs (fly ash, slag)	Material	Reduce C3A and CH, refine pores	High
Sulfate-resistant cement	material	lower C3A content	High
Low w/c ratio	Mix design	Reduce permeability	High
Protective coatings	Surface protection	Prevent water/ion ingress	Medium
Soil replacement	Geotechnical	Remove sulfate source	High
Membrane systems	Barrier	Isolate concrete from soil	Medium–High

6. Results and Discussion

In our review of experimental data we see that which trends we modeled in Figure 1 are played out. In hybrid NS-RPB systems we noted a very quick initial gain in strength. Also from our review of the literature, we see that in hybrid mixes peak strength is achieved at an earlier date in comparison to RBP only mixes. This is put down to the high reactivity of NS. Also we found that in terms of strength loss over 90 days of sulfate exposure the hybrid mixes did very well and had almost no regression in strength. In contrast RBP only mixes often see a 10 to 15% strength reduction due to sulfate attack. Integration of NS into the mix reduced pore connectivity which is a key factor in resistance to sulfate attack. Also by dense packing the matrix we see that diffusion of sulfate ions is greatly reduced which in turn prevents the chemical reactions listed in Table 1. In Table 2 we present that the hybrid approach is the best. Although cement does very well in terms of initial strength what it lacks is durability under sulfate exposure which the NS-RBP blend does better in. The hybrid mix what it does is it takes the volume stability of RBP and the pore refining capability of NS. Also in research done in Iraqi settings it is reported that the local clay mineralogy has a very good reaction with these additives which supports our results. This review reports that, as also presented in recent regional studies, traditional stabilization methods do not perform adequately in high-sulfate environments due to the absence of durable design approaches. Also, in the case of the Iraqi environment, recent literature reports on the performance of supplementary cementitious materials such as fly ash and calcined clay that play a role in enhancing sulfate resistance, which they do by reducing matrix permeability. But what this study puts forth is a better alternative. We introduce a hybrid NS-RBP system that includes the microstructural benefits of nano silica and the chemical stability of recycled brick powder. This, in turn, enables it to put a dent in the internal expansive pressures, which is what we see to cause structural failures in our local infrastructure.

7. Conclusions

In this critical review we present that which follows in terms of our study on the durability of expansive clay: Synergistic Action: We see that the use of NS and RBP together does an excellent job at presenting a solution to the two main issues of swell pressure and sulfate attack. RBP we note for is that is has lasting pozzolanic action and at the same time NS' role is to improve matrix density. Sulfate Resilience: Mainly what we see is that RBP improves the material by way of physical reduction of pore size and also by way of chemical stabilization of the alumina phases which in turn prevents ettringite formation. Also of note is that from a sustainability point of view we put forth that the use of RBP is very much in line with world wide goals for sustainability, by way of recycling construction waste, and also a green alternative to cement based deep mixing.

References

[1] Zhang, Y., Liu, K., & Wang, D. (2023). Swelling behavior and stabilization mechanisms of expansive soils: A comprehensive review. Engineering Geology, 321, 107145.

[2] Li, J., Chen, Q., & Xu, H. (2024). Advances in mitigation strategies for expansive clay soils. Applied Clay Science, 243, 107035.

[3] Wang, T., Zhao, S., & Li, X. (2022). Mechanisms of sulfate attack in cement-stabilized soils: Microstructural and durability perspectives. Construction and Building Materials, 344, 128256.

[4] Puppala, A. J., & Pedarla, A. (2023). Sulfate-induced heave in chemically treated geomaterials. Transportation Geotechnics, 39, 100897.

[5] Skaropoulou, A., & Tsivilis, S. (2022). Thaumasite formation and durability performance in sulfate environments. Cement and Concrete Research, 158, 106850.

[6] Liu, R., Zhang, M., & Yang, J. (2024). Long-term performance of cement-treated sulfate-bearing soils. Construction and Building Materials, 389, 131755.

[7] Hussein, S.S, Abdullah. O. H., & Abdulsamad, A. A. (2026). Engineering performance of sulfate-bearing soils in Iraq and their impact on concrete foundations: Mechanisms, evaluation methods, and mitigation approaches: A critical review. Al-Rafidain journal of engineering science, 4(1), 531-539.

[8] García-Sánchez, F., & Treviño, A. (2023). Sustainable soil improvement using recycled brick waste. Journal of Cleaner Production, 382, 135268.

[9] Zhao, Y., Sun, W., & Li, H. (2024). Mechanical and microstructural properties of expansive soils stabilized with recycled brick powder. Applied Clay Science, 240, 106982.

[10] Singh, L. P., Bhattacharyya, S. K., & Mishra, G. (2023). Nano-silica in geomaterials: Microstructure, durability, and sustainability assessment. Materials, 16(4), 1425.

[11] Al-Harthy, A., & Al-Shamrani, M. (2024). Nano-modified binders for sulfate-resistant soil stabilization. Construction and Building Materials, 401, 132908.

[12] Chen, X., Huang, Y., & Zhou, W. (2025). Coupled effects of nano-silica and supplementary binders on durability of clay soils. Engineering Geology, 335, 107470.