Journal Homepage: www.ijarpr.com ISSN: 3049-0103 (Online)

International Journal of Advance Research Publication and Reviews

Vol 03, Issue 8, pp 608-618, August, 2026

Sustainable Stabilization of Expansive Soil Using Industrial By-Products and Bio-Based Additives

[1]HEMANT KUMAR AGRAWAL, [2] SUNIL KUMAR

[1,2] ASSISTANT PROFESSOR
JAGANNATH UNIVERSITY, JAIPUR
Email id – hemantk.agrawal@jagannathuniversity.org

DOI : https://doi.org/10.5281/zenodo.22093683

ABSTRACT—

Expansive soils undergo pronounced swell–shrink deformation with seasonal moisture variation, creating differential heave, loss of bearing capacity, pavement distortion, and foundation distress. Conventional lime and Portland-cement stabilization is effective, but its embodied-energy and carbon burden has accelerated interest in circular and bio-derived alternatives. This paper presents an IEEE-style critical synthesis and proposed experimental framework for stabilizing expansive soil using industrial by-products—principally fly ash, ground-granulated blast-furnace slag (GGBS), steel slag, rice-husk ash, and related mineral residues—together with bio-based additives such as xanthan gum, guar gum, and lignin. Published evidence indicates that fly ash dosages in the range of 25–40% can substantially improve plasticity, strength, penetration resistance, swell behavior, and compressibility, while FA–GGBS systems provide additional latent-hydraulic and geopolymeric bonding. Biopolymers act through hydrogel formation, hydrogen bonding, pore filling, and particle bridging, offering a complementary mechanism to inorganic cementation. The manuscript develops a hybrid stabilization hypothesis in which an industrial binder supplies durable mineral bonding and a low-dose biopolymer improves early cohesion, moisture resistance, and particle connectivity. A structured testing program is proposed covering Atterberg limits, compaction, free swell/swell pressure, unconfined compressive strength (UCS), California Bearing Ratio (CBR), wet–dry durability, microstructure, and environmental screening. Equations, literature-derived performance graphs, comparative tables, and a multi-criteria sustainability index are included. The synthesis identifies curing regime, binder chemistry, biopolymer dosage, durability, and leachability as the principal variables that must be resolved before large-scale field adoption.

Index Terms—*expansive soil, black cotton soil, fly ash, GGBS, industrial by-products, biopolymer, xanthan gum, guar gum, lignin, soil stabilization, UCS, CBR, sustainability.*

I. INTRODUCTION

Expansive soils are fine-grained geomaterials whose volume is strongly coupled to water content and suction. Smectitic minerals, particularly montmorillonite-rich assemblages, possess large specific surface area and exchangeable interlayer cations; hydration causes diffuse-double-layer expansion and osmotic swelling, whereas drying promotes contraction and cracking. The resulting cyclic deformation can generate differential heave beneath lightly loaded foundations, distort road subgrades, rupture buried utilities, and progressively degrade slope and embankment performance. The engineering challenge is therefore not merely low strength: it is the coexistence of moisture sensitivity, plasticity, swell pressure, shrinkage, and time-dependent fabric change [1], [2].

Chemical stabilization with lime or cement reduces plasticity and develops cementitious bonds, but sustainability objectives increasingly favor partial or complete substitution with industrial and agricultural by-products. Fly ash, GGBS, steel slag, cement-kiln dust, silica fume, red mud, and similar residues contain reactive silica, alumina, and calcium phases capable of cation exchange, flocculation, hydration, pozzolanic reaction, or geopolymerization. Their reuse can simultaneously divert large waste streams and reduce demand for virgin binders. Recent reviews report that appropriately designed industrial-waste systems can increase UCS and CBR while decreasing swelling and compressibility [3], [4].

A parallel research direction uses bio-based binders. Xanthan gum and guar gum form viscous hydrogels and dehydrated polymer films that bridge particles and occupy pore spaces; lignin-rich coproducts can produce adhesive or cementing effects and reduce water infiltration. Unlike calcium-based stabilization, these treatments may not rely on formation of C-S-H. Their performance therefore depends strongly on polymer chemistry, water content, curing humidity, temperature, and biodegradation resistance [6]–[10]. The distinct mechanisms suggest a useful hybrid concept: industrial by-products can provide mineralogical stability and long-term cementation, while a small bio-additive fraction can improve cohesion, particle bridging, erosion resistance, and moisture management.

The purpose of this manuscript is fourfold. First, it synthesizes current evidence on industrial and bio-based expansive-soil stabilization in a form suitable for engineering design discussion. Second, it explains the mechanisms that govern index, compaction, strength, swell, and durability responses. Third, it proposes a reproducible experimental matrix for evaluating hybrid industrial–bio systems. Fourth, it introduces a transparent multi-criteria framework that balances engineering performance with circularity, environmental risk, durability maturity, and field readiness. The work is deliberately presented as a literature-synthesis and research-design paper; numerical values identified as literature data are not represented as new laboratory measurements.

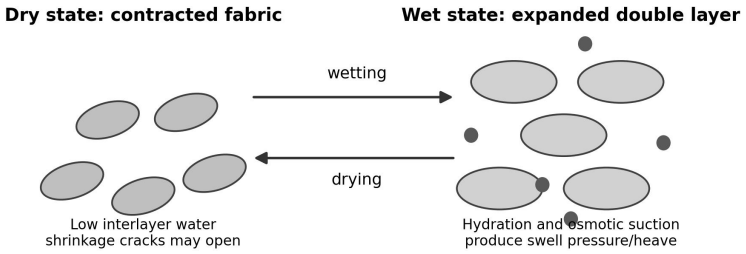

Fig. 1. Schematic representation of the moisture-driven swell–shrink cycle in expansive clay (original diagram).

II. RESEARCH NEED, GAP, AND OBJECTIVES

Most studies investigate either mineral waste stabilization or biopolymer treatment independently. Industrial by-products have comparatively mature strength and microstructural evidence, but their performance varies with source chemistry and often requires calcium availability or alkaline activation. Biopolymers offer low dosage and potentially low embodied carbon, yet their durability under wet–dry cycling, biological exposure, and sustained saturation remains less certain. A hybrid mixture can theoretically address these weaknesses, but the interaction between inorganic reaction products and organic polymer films is not sufficiently standardized.

Three gaps are especially important. The first is mechanistic: it is unclear whether polymer films inhibit reactive surfaces when added too early or at excessive dosage, or whether they instead improve dispersion and contact during compaction. The second is durability: strength obtained in air curing may not persist under laboratory-moist or immersed conditions, as highlighted by recent black-cotton-soil biopolymer testing [10]. The third is sustainability verification: diverting a waste material is not automatically sustainable if the material introduces leachable contaminants, high activator demand, difficult field mixing, or short service life.

Accordingly, the proposed research objectives are: (1) quantify how selected industrial by-products and bio-additives change plasticity, compaction, swell pressure, UCS, and CBR; (2) identify an optimum hybrid dosage using performance and sustainability criteria; (3) relate macro-scale response to SEM/XRD/FTIR evidence; (4) evaluate wet–dry durability and moisture sensitivity; and (5) define an implementation envelope suitable for pavement subgrade and shallow-foundation applications.

TABLE I. ENGINEERING PROBLEMS AND PERFORMANCE TARGETS

Problem	Engineering consequence	Primary response metric
High plasticity	Poor workability and moisture sensitivity	LL, PL, PI
Swell–shrink cycling	Heave, cracking, differential movement	Free swell, swell pressure, volumetric strain
Low bearing resistance	Pavement rutting and subgrade deformation	CBR, resilient/strength indicators
Low cohesive strength	Shear failure and weak compacted layer	UCS, direct shear
High compressibility	Settlement and loss of level	Compression index / constrained modulus
Durability loss	Strength reduction after seasonal cycles	Retained UCS/CBR after wet–dry cycles
Environmental risk	Leaching or unsuitable waste reuse	pH, leachability, source characterization

III. MATERIALS FOR SUSTAINABLE STABILIZATION

A. Industrial By-Products

Fly ash (FA) is one of the most widely examined by-products for expansive-soil treatment. Class C material contains greater self-cementing calcium, whereas Class F fly ash is generally more siliceous and often benefits from an activator or calcium-rich co-binder. A 2024 review found that 25–40% fly ash, across the studies it synthesized, produced reported improvements of approximately 30–33% in plastic behavior, 40–48% in compressive/shear strength, 52–55% in penetration resistance, 42–48% in swelling response, and 36–40% in compressibility [3]. These values are not universal design constants; they show the scale of improvement that can be achieved when soil mineralogy, ash chemistry, dosage, moisture, and curing are favorable.

GGBS is a glassy, calcium-rich latent hydraulic material generated during iron production. Compared with low-calcium fly ash, it can accelerate early reaction and increase the supply of calcium for C-S-H/C-A-S-H type gels. Sharma and Sivapullaiah demonstrated the potential of FA–GGBS blends for expansive-soil stabilization, while later reviews summarized 28-day UCS ranges for selected GGBS and FA–GGBS treatments [4], [5]. More recent geopolymer literature reports still higher strengths when alkaline activation is used, but activator handling, leachability, and carbon accounting must be considered [11].

Steel slag, cement-kiln dust (CKD), silica fume, red mud, and phosphogypsum can also modify clay behavior. Calcium-bearing wastes favor ion exchange, flocculation, and hydration; highly siliceous materials often act as pozzolans or fillers. However, industrial residues are heterogeneous. Before field use, the engineering program should include oxide composition, mineral phases, fineness, pH, loss on ignition, soluble salts, and contaminant screening. The sustainability benefit derives from appropriate reuse, not from the waste label itself [4], [12].

TABLE II. INDUSTRIAL BY-PRODUCTS FOR EXPANSIVE-SOIL STABILIZATION

Material	Dominant role	Advantages	Key cautions
Fly ash	Pozzolanic / filler / cation exchange	Large-volume reuse; plasticity and swell reduction	Source variability; low-Ca ash may need activation
GGBS	Latent hydraulic binder	Early and long-term strength; works well with FA	Grinding/transport burden; sulfate chemistry
Steel slag	Alkaline Ca-rich granular/binder phase	Strength, density, waste diversion	Expansion and metal/leachability screening
CKD	Highly alkaline activator/binder	Fast reaction; calcium supply	High pH; variable alkalis and

Material	Dominant role	Advantages	Key cautions
			salts
Rice-husk ash	Siliceous agricultural ash	Low density; reactive silica after controlled burning	Quality depends strongly on burn temperature
Red mud / PG	Reactive residue / chemical modifier	Potential circular use in selected systems	Environmental and radiological/leachability checks essential

B. Bio-Based Additives

Xanthan gum is an anionic microbial polysaccharide produced by fermentation. In water it forms a highly viscous hydrogel, and after drying it can form flexible films around and between soil particles. Reported geotechnical benefits include strength gain, erosion resistance, water retention, and permeability reduction [7], [8]. For expansive clay, the response is particularly sensitive to curing: field-like drying can increase interparticle bonding, whereas persistent laboratory moisture may retain the polymer in a hydrogel state and reduce effective particle contact [10].

Guar gum is a plant-derived galactomannan. Sujatha and Saisree reported that guar gum changed compaction behavior only modestly but substantially increased UCS with content and curing; for 2% guar gum, the strength of the treated soil increased from 221.7 kPa without curing to 463.6 kPa after 90 days [6]. The mechanism was attributed to hydrogel formation, pore filling, dehydration, and hydrogen bonding. The material is attractive because it is renewable and effective at low dosage, but water sensitivity and biodegradation remain design considerations.

Lignin is an aromatic biopolymer generated in large quantities by pulp, paper, and bioenergy operations. Lignin-rich coproducts can coat and bind soil particles and reduce water infiltration. Experimental work on expansive subgrade soils has shown that an optimum lignin content can reduce swell–shrink potential and alter water-retention behavior, with microstructural evidence of pore filling and particle bonding [9]. Lignin is particularly relevant to a hybrid concept because it is itself an industrial bio-coproduct and can contribute both circularity and hydrophobic/adhesive effects.

TABLE III. BIO-BASED ADDITIVES AND EXPECTED MECHANISMS

Additive	Typical dosage scale	Primary mechanism	Principal limitation
Xanthan gum	≈0.25–1.5% of dry soil	Viscous hydrogel, film formation, particle bridging	Moist-curing sensitivity and cost at high dosage
Guar gum	≈0.25–2.0%	Hydrogen bonding, hydrocolloid network, pore filling	Biodegradation and wet durability
Lignin/lignosulfonate	Low single-digit % (source dependent)	Adhesive bonding, pore filling, moisture control	Chemistry varies with production process
Starch/chitosan derivatives	Low %; formulation dependent	Gelation, electrostatic attraction, particle coating	Durability and scalability need verification

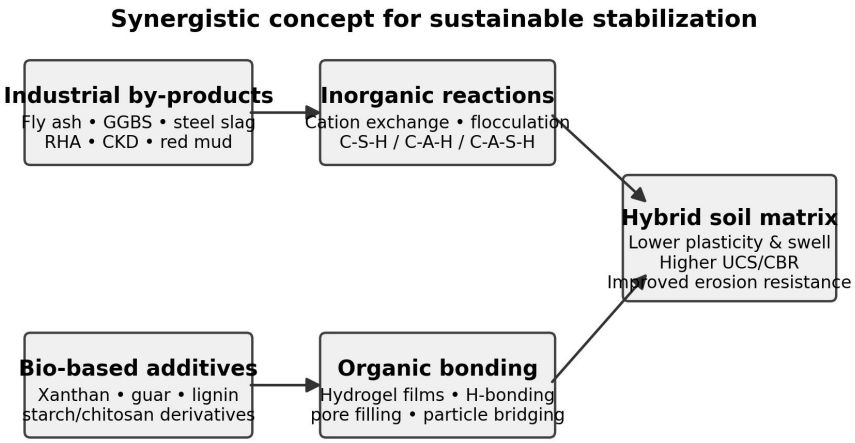

Fig. 2. Proposed synergistic mechanism for a hybrid industrial by-product and bio-additive stabilization system (original diagram).

IV. STABILIZATION MECHANISMS

A. Cation Exchange and Flocculation

Expansive clay surfaces commonly carry net negative charge. Calcium and magnesium released from alkaline waste binders can replace monovalent exchangeable cations, compress the diffuse double layer, and reduce repulsive forces between clay platelets. The immediate engineering effect is usually a reduction in plasticity and increased friability. Particle association shifts from dispersed to flocculated–agglomerated fabric, making the soil easier to compact and less susceptible to moisture-driven rearrangement [4].

Although cation exchange is fast, it is not itself sufficient for durable high strength. Long-term performance requires stable bonding or matrix densification. Therefore, the availability of soluble silica, alumina, calcium, pH, and curing water controls the subsequent development of cementitious products.

B. Pozzolanic, Hydraulic, and Geopolymeric Bonding

In calcium-rich systems, dissolved silica and alumina react in an alkaline environment to form calcium-silicate-hydrate (C-S-H), calcium-aluminate-hydrate (C-A-H), and mixed C-A-S-H phases. These products occupy void space, coat particles, and create rigid interparticle bridges. In low-calcium FA systems, GGBS or CKD can supply calcium and raise alkalinity. When strong alkaline activators are used, aluminosilicate dissolution and

polymerization can also create N-A-S-H or hybrid gels. A simplified reaction description is:

$$Ca(OH)_2 \rightarrow Ca^{2+} + 2OH^- \quad (1)$$

$$Ca^{2+} + OH^- + SiO_2(aq) \rightarrow C\text{–}S\text{–}H\ gel \quad (2)$$

$$Ca^{2+} + OH^- + Al_2O_3(aq) \rightarrow C\text{–}A\text{–}H\ gel \quad (3)$$

The equations are schematic rather than stoichiometrically complete mineral reactions. They are useful for linking chemical availability to the engineering response: more stable cementitious bonding generally increases UCS and CBR, reduces compressibility, and limits water-accessible void space. Excess additive, however, may introduce unreacted particles, brittle behavior, higher water demand, or undesirable salts.

C. Biopolymer Hydrogel and Film Bonding

Biopolymer strengthening is physically and chemically distinct. Polysaccharide chains contain functional groups capable of hydrogen bonding with water and mineral surfaces. During mixing, the hydrated polymer increases viscosity and coats particles; during drying, water is removed and the polymer network becomes denser, creating bridges across particle contacts. In clay, the network can fill voids and restrain platelet movement. This explains why curing humidity is a first-order variable rather than a secondary test condition [6], [10].

At excessive dosage, a highly viscous polymer solution can make uniform mixing difficult, separate particles, or retain too much water. Consequently, the optimum dosage is expected to be lower in a hybrid system than when the biopolymer acts as the sole binder. A low polymer fraction can provide early cohesion and erosion resistance while leaving sufficient mineral surface accessible for inorganic reactions.

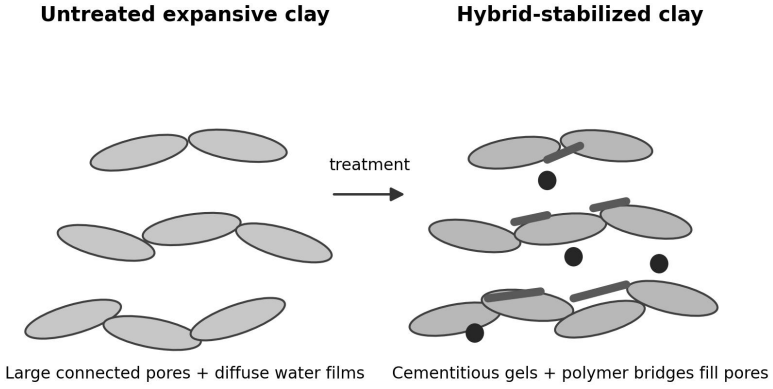

Fig. 3. Conceptual microstructural evolution from an untreated clay fabric to a hybrid matrix containing mineral gels and polymer bridges (original schematic).

V. PERFORMANCE INDICES AND GOVERNING EQUATIONS

The experimental program should use dimensionless performance indices so that mixtures with different baseline soils can be compared. The following equations are recommended. LL and PL denote liquid and plastic limits; S is a swell metric; q_u is UCS; P is measured CBR penetration load; γ and γd are bulk and dry unit weight; w is gravimetric water content.

$$PI = LL - PL \quad (4)$$

$$R_s = [(S_0 - S_t) / S_0] \times 100 \quad (5)$$

$$I_{uc\ s} = [(q_{u,t} - q_{u,0}) / q_{u,0}] \times 100 \quad (6)$$

$$CBR = (P_t / P_{st}d) \times 100 \quad (7)$$

$$\gamma d = \gamma / (1 + w) \quad (8)$$

$$B = (m\_binder / m\_dry\ soil) \times 100 \quad (9)$$

$$A\_bio = (m\_bio / m\_dry\ soil) \times 100 \quad (10)$$

For sustainability screening, a composite index can combine normalized technical and environmental terms. Let n_i be a 0–100 normalized score and w_i its weight, with $\Sigma w_i = 1$:

$$CSI = \Sigma\ (w_i\ n_i) \quad (11)$$

For a performance-oriented study, suggested weights are 0.25 for strength/bearing, 0.20 for swell control, 0.20 for circularity and embodied-carbon reduction, 0.15 for durability, 0.10 for constructability, and 0.10 for environmental risk. The weighting should be declared before optimization to prevent post-hoc selection of a preferred mixture.

VI. LITERATURE-DERIVED PERFORMANCE SYNTHESIS

Figure 4 summarizes the ranges reported in a 2024 fly-ash review [3]. Because the underlying studies use different soils, ash classes, curing conditions, and test procedures, the figure should be interpreted as a literature envelope rather than a pooled statistical effect size. Nevertheless, it demonstrates a consistent pattern: waste-derived mineral binders can address both the strength deficit and the volumetric instability of expansive soil.

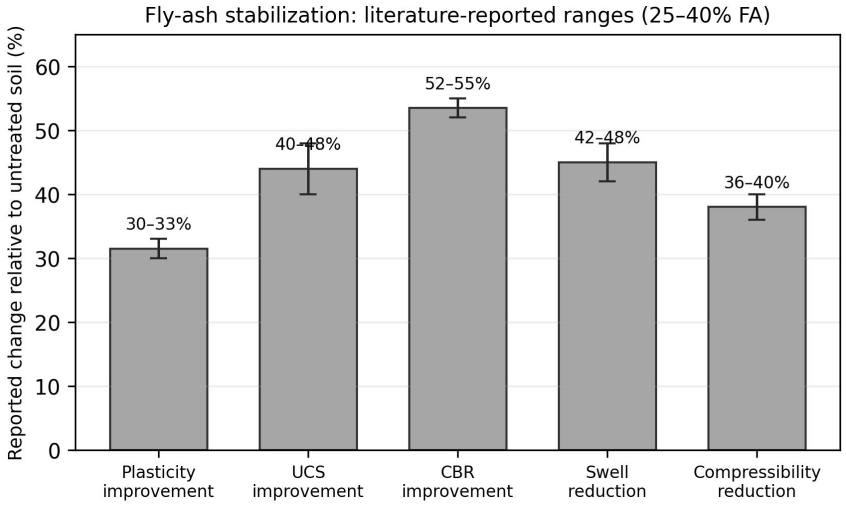

Fig. 4. Literature-reported performance ranges for expansive soils treated with 25–40% fly ash, reconstructed from the synthesis in [3].

The role of GGBS is evident in strength data summarized by Wei et al. [4]. Their review lists 28-day UCS ranges of approximately 0.67–1.14 MPa for a 30% GGBS treatment in one cited CH soil and approximately 0.27–0.45 MPa for a 6% FA + 14% GGBS mixture in another dataset. Such values should not be directly transferred between sites, but they support the mechanism of calcium-assisted mineral bonding. In highly activated FA–GGBS geopolymer systems, a 2026 review reports a much broader 28-day UCS envelope of 2.27–9.5 MPa and substantial CBR gains, confirming that binder chemistry and activation intensity can dominate performance [11].

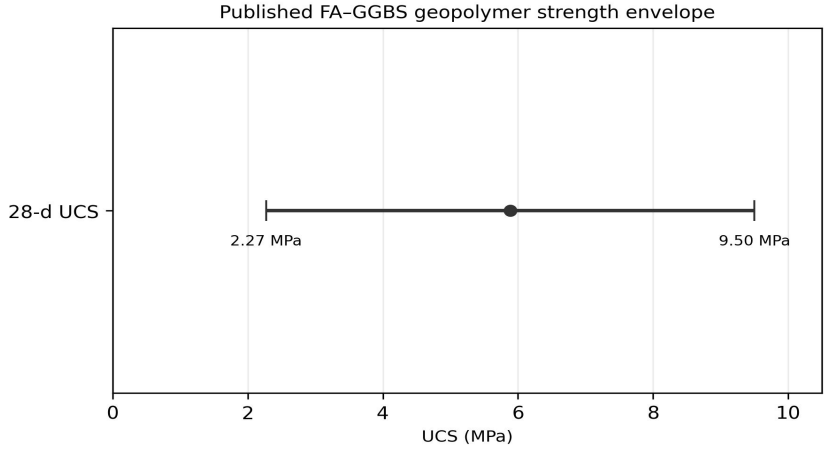

Fig. 5. Reported 28-day UCS envelope for FA–GGBS geopolymer-treated expansive soils summarized in a 2026 review [11].

Biopolymer data show a different response pattern. Guar gum strength increases with curing as the hydrogel network dehydrates and strengthens. The two-point trend in Fig. 6 is based on the 2% guar-gum data reported by Sujatha and Saisree [6]. Recent black-cotton-soil work further shows that curing environment can change the outcome: at an optimum 1.5% biopolymer dosage, field-curing conditions produced a maximum normalized compressive-strength response of up to 4.18 times the untreated soil, whereas laboratory-moist curing produced much lower improvement and could lose strength with time [10]. This result is central to hybrid design because it means that a polymer-only optimum measured under one humidity condition may not be transferable to another.

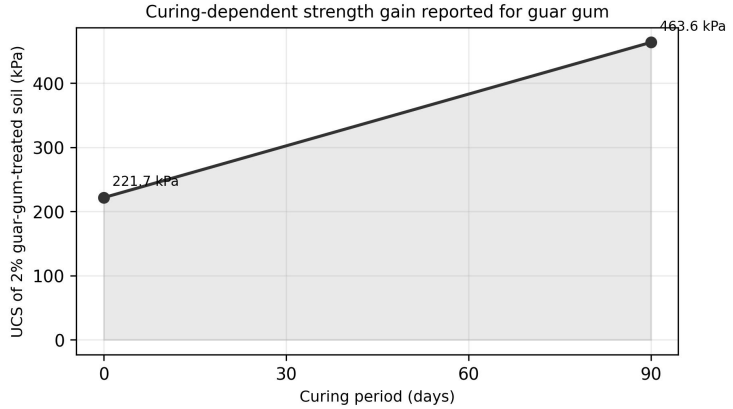

Fig. 6. Curing-dependent UCS increase reported for soil treated with 2% guar gum [6].

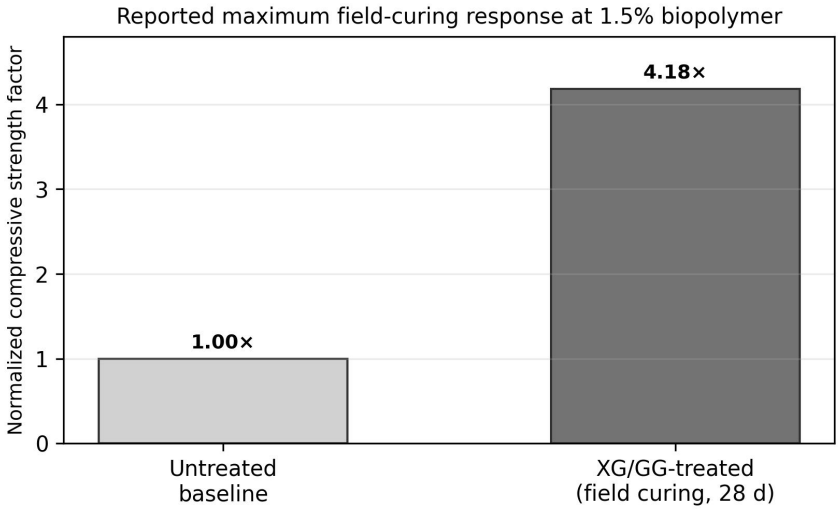

Fig. 7. Maximum normalized compressive-strength factor reported under field curing at 1.5% xanthan/guar treatment in black cotton soil [10].

TABLE IV. SELECTED LITERATURE EVIDENCE USED IN THIS SYNTHESIS

System	Dose/condition	Reported response	Source
Fly ash	25–40% across reviewed studies	Plastic behavior +30–33%; strength +40–48%; CBR/penetration +52–55%; swelling reduced 42–48%	[3]
GGBS	30%; CH soil in reviewed dataset	28-d UCS ≈0.67–1.14 MPa	[4]
FA + GGBS	6% FA + 14% GGBS	28-d UCS ≈0.27–0.45 MPa	[4]
FA–GGBS geopolymer	Various activated systems	28-d UCS ≈2.27–9.5 MPa; CBR 9–416% across reviewed studies	[11]
Guar gum	2%	UCS 221.7 → 463.6 kPa from 0 to 90 d curing	[6]
Xanthan/guar	1.5%; field curing	Up to 4.18× untreated compressive strength at 28 d	[10]
Lignin coproduct	Optimum content, study-specific	Reduced swell–shrink behavior; particle bonding/pore filling observed	[9]

VII. PROPOSED HYBRID EXPERIMENTAL PROGRAM

A. Soil and Additive Characterization

A representative expansive soil should be collected below the organic-rich surface horizon, air dried, pulverized, and passed through the sieve required by each test. Initial characterization should include particle-size distribution, specific gravity, Atterberg limits, standard Proctor compaction, free swell or one-dimensional swell pressure, UCS, and soaked/unsoaked CBR where appropriate. Mineralogy should be established using XRD, and the clay fraction should be assessed for smectitic behavior. This baseline is essential because identical additive dosages can produce different responses in soils with different clay activity and exchange capacity.

Industrial by-products should be analyzed for particle size, specific gravity, pH, oxide composition (XRF), and crystalline/amorphous phases (XRD). Where steel slag, red mud, CKD, phosphogypsum, or other chemically complex residues are considered, leachability and soluble-salt testing should be added. Biopolymers should be recorded by supplier grade, moisture content, solution concentration, viscosity preparation procedure, and mixing temperature. Reproducibility requires more than reporting “1% xanthan”; the hydration protocol can change the apparent dosage response.

B. Proposed Mix Matrix

A staged design is preferable to testing every possible combination. Stage 1 screens industrial-binder ratios; Stage 2 adds low-dose biopolymer to the two best inorganic systems; Stage 3 subjects the best-performing mixes to durability and microstructural tests. The matrix below is designed for a black-cotton/CH-type soil and can be adjusted after preliminary pH and compaction trials.

TABLE V. PROPOSED MIX MATRIX (PERCENT OF DRY SOIL MASS)

Mix	FA/RHA (%)	GGBS (%)	Bio-additive	Bio (%)	Purpose
M0	0	0	0	0	Untreated control
M1	20	0	0	0	FA baseline
M2	0	20	0	0	GGBS baseline
M3	10	10	0	0	Balanced FA–GGBS
M4	15	5	0	0	FA-rich blend
M5	5	15	0	0	GGBS-rich blend
M6	10	10	XG	0.50	Hybrid low XG
M7	10	10	XG	1.00	Hybrid medium XG
M8	10	10	GG	0.50	Hybrid low GG
M9	10	10	GG	1.00	Hybrid medium GG
M10	15	5	Lignin	1.00	FA-rich + lignin
M11	5	15	Lignin	1.00	GGBS-rich + lignin
M12	10 RHA	10	XG	0.50	Alternative ash hybrid
M13	10	10	GG	1.50	Upper polymer check

C. Mixing and Curing Protocol

Dry mineral binders should first be blended with the air-dried soil until visually uniform. The biopolymer should be introduced using a controlled method selected during pilot mixing: either as a pre-hydrated solution or as a dry powder followed by water. For xanthan and guar, pre-hydration usually provides better chain dispersion but can produce localized high viscosity if added too quickly. Mixing water should be adjusted to the target molding water content, and specimens should be compacted at a specified fraction of the maximum dry density from the relevant mix-specific compaction curve.

Curing should deliberately separate mechanisms. Recommended conditions are: sealed curing to retain moisture; laboratory-air curing; and field-representative curing under recorded temperature/humidity. Suggested ages are 0, 7, 28, and 90 days for UCS, with at least 7 and 28 days for the main screening phase. The cure condition must be reported together with age because biopolymer performance can reverse with moisture state [10].

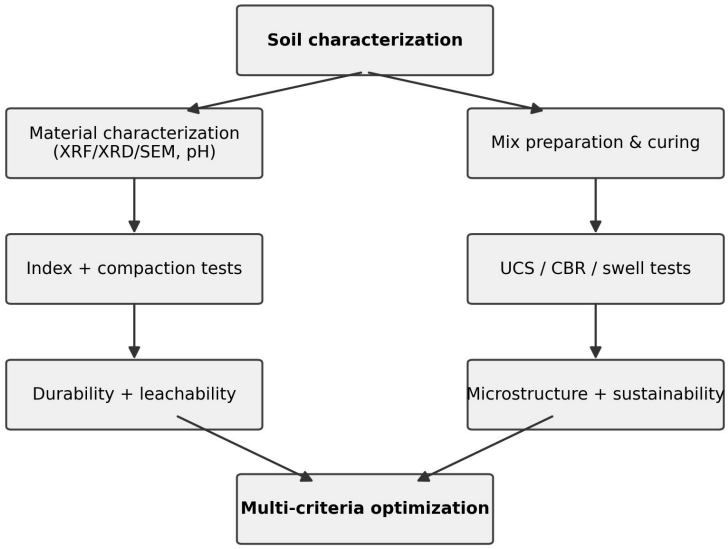

Fig. 8. Proposed experimental workflow for hybrid stabilization, from material characterization through multi-criteria optimization (original flowchart).

D. Testing Standards and Response Matrix

TABLE VI. RECOMMENDED LABORATORY TEST PROGRAM

Property	Recommended method	Purpose
Atterberg limits	ASTM D4318	Plasticity modification and workability
Standard compaction	ASTM D698	MDD–OMC relationship for each candidate mix
Unconfined compression	ASTM D2166/D2166M	Strength gain, stress–strain response, curing effect
California Bearing Ratio	ASTM D1883	Subgrade bearing response; soaked condition preferred for moisture sensitivity
One-dimensional swell	ASTM D4546 or project-equivalent	Swell/collapse strain or swell pressure
Wet–dry durability	Project protocol / applicable local standard	Strength retention and cracking after cyclic moisture
Microstructure	SEM + XRD; FTIR where bio-additives are used	Identify gels, particle bonding, polymer functional interactions
Environmental screening	pH + leachability for selected industrial residues	Confirm safe reuse and identify contaminant constraints

VIII. PROPOSED DATA ANALYSIS AND OPTIMIZATION

A. Screening Logic

The optimum mix should not be selected by maximum UCS alone. A very high binder content may deliver strong specimens but poor sustainability, high cost, excessive stiffness, or greater environmental risk. Conversely, the lowest-carbon mixture may lack wet durability. The proposed screening method first rejects mixtures that fail minimum swell and bearing criteria, then ranks the remaining mixtures by a composite sustainability-performance index.

Figure 9 illustrates an author-defined design-screening surface, not measured data. It assumes that moderate industrial-binder contents (roughly 20–25%) and low bio-additive contents (roughly 0.5–1.0%) are likely to provide the best balance between mineral reaction, polymer bridging, workability, and material efficiency. The purpose of the plot is to guide efficient testing, not to prescribe an optimum dosage.

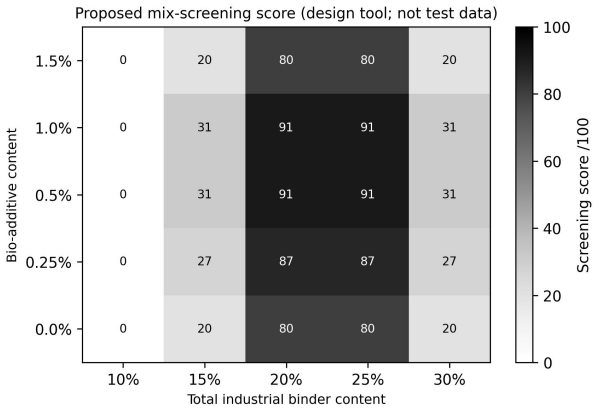

Fig. 9. Proposed hybrid mix-screening surface. Values are author-defined design scores, not experimental measurements.

B. Illustrative Calculation

Consider an illustrative mixture for which the untreated soil has a swell index S_0 = 18% and UCS $q_u,0$ = 0.25 MPa, while the treated specimen has S_t = 9.9% and q_u,t = 0.36 MPa. These values are used only to demonstrate the calculation method. From (5), the swell reduction is 45%. From (6), the UCS improvement is 44%. If the same mix receives normalized scores of 85 for strength/bearing, 80 for swell control, 95 for circularity/carbon, 70 for durability, 80 for constructability, and 75 for environmental risk, the weighted CSI using the weights stated earlier is:

$$\mathbf{CSI = 0.25(85)+0.20(80)+0.20(95)+0.15(70)+0.10(80)+0.10(75) = 82.25} \quad \mathbf{(12)}$$

The calculation makes the trade-off explicit and prevents a mixture with a single exceptional property from dominating the decision. Sensitivity analysis should then vary the weights according to project type; for example, a road subgrade may weight soaked CBR and wet durability more heavily, whereas a foundation pad may weight swell pressure and stiffness.

IX. SUSTAINABILITY AND ENVIRONMENTAL ASSESSMENT

Sustainability in soil stabilization has at least five dimensions: reduced virgin-binder demand, diversion of industrial or agricultural residues, reduction in embodied greenhouse-gas emissions, service-life extension, and avoidance of new environmental hazards. Industrial by-products score strongly in circularity when they are locally available and replace high-impact binders. Bio-based additives can further reduce mineral-binder demand because they are effective at comparatively low dosage. However, transport distance, preprocessing energy, activator production, and replacement efficiency must be included in any life-cycle comparison.

FA–GGBS geopolymer literature suggests the potential for major CO_2 reduction relative to Portland-cement stabilization when the system is efficiently activated and local materials are used [11]. That potential does not eliminate the environmental burden of sodium silicate, sodium hydroxide, grinding, or curing. A hybrid system that achieves acceptable performance without aggressive alkaline activation may therefore be preferable even if its peak laboratory strength is lower.

Leachability is particularly important when steel slag, red mud, phosphogypsum, CKD, or mixed industrial residues are used. The stabilizer must not create groundwater risk merely to solve a geotechnical problem. Source-specific testing should accompany engineering testing, and any project using chemically complex wastes should establish acceptance limits based on local environmental regulation.

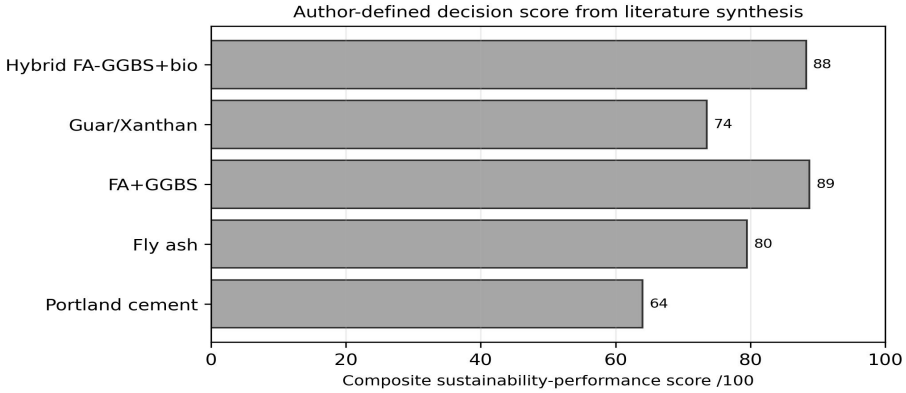

Fig. 10. Author-defined composite sustainability-performance screening scores derived from qualitative literature evidence; values are decision aids, not measured life-cycle results.

TABLE VII. MULTI-CRITERIA DECISION FRAMEWORK

Criterion	Suggested weight	Preferred direction	Evidence
Strength / bearing performance	0.25	Higher UCS/CBR with acceptable ductility	UCS, CBR, stress–strain
Swell control	0.20	Lower free swell/swell pressure	Swell and wetting tests
Circularity / carbon	0.20	More waste substitution; lower virgin binder	Material inventory / LCA screen

Criterion	Suggested weight	Preferred direction	Evidence
Durability	0.15	Higher retained strength after moisture cycling	Wet–dry and soak retention
Constructability	0.10	Easy mixing/compaction and realistic curing	Workability and field trial
Environmental risk	0.10	Lower leaching and benign pH/chemistry	Leachability and source data

X. EXPECTED HYBRID INTERACTIONS AND DESIGN HYPOTHESES

- Hypothesis H1—Low-dose biopolymer will increase early cohesion and reduce erosion sensitivity of FA–GGBS-treated soil without materially reducing mineral reaction, provided the polymer dosage remains below the point at which a continuous viscous film isolates reactive mineral surfaces.
- Hypothesis H2—GGBS-rich blends will deliver higher early UCS than FA-rich blends because of greater calcium availability and latent hydraulic reactivity, while FA-rich blends may offer improved circularity and lower density. The optimum ratio will depend on ash class and soil mineralogy.
- Hypothesis H3—Air or field curing will favor polymer film formation and may therefore produce higher strength than persistently moist laboratory curing. Mineral-binder reactions, however, require adequate water. A hybrid system should therefore exhibit an optimum curing-moisture window rather than a monotonic drying benefit.
- Hypothesis H4—The most sustainable mixture will not necessarily coincide with maximum UCS. A moderate binder content plus 0.5–1.0% bio-additive is expected to provide a better weighted balance of swell control, strength, circularity, and constructability than either a high-binder inorganic mixture or a high-dose polymer-only mixture.
- Hypothesis H5—Durability will be governed by the continuity of the inorganic skeleton after partial polymer softening or biodegradation. This is the principal reason to prefer a hybrid architecture for long-service infrastructure: mineral reaction products provide a persistent load-transfer path even if the organic phase changes with time.

XI. PRACTICAL FIELD IMPLEMENTATION

Field implementation should begin with a short test strip rather than immediate full-scale adoption. The sequence is: scarify the expansive subgrade to design depth; spread and dry-mix industrial binder; spray a controlled biopolymer solution where used; remix to uniformity; adjust water to the target molding range; compact within the established working time; and cure using a protocol compatible with both the mineral and bio phases. Moisture control is critical because excessive water can suppress polymer film formation while insufficient water can limit mineral reaction and compaction.

Quality-control measurements should include additive application rate, field moisture content, in-place density, surface uniformity, and selected field strength or stiffness indicators. Laboratory companion specimens prepared from the same materials should verify UCS/CBR and wet durability. For pavement applications, drainage must still be addressed: stabilization reduces sensitivity but does not justify poor surface or subsurface drainage.

Constructability may favor dry or powdered lignin-type additives for remote projects, whereas pre-hydrated xanthan or guar may be attractive where controlled mixing water is readily available. The field decision should consider local material supply, storage stability, temperature sensitivity, and worker handling. A lower-performance local waste that requires little transport may be more sustainable than a high-performance binder shipped over long distance.

TABLE VIII. PRELIMINARY FIELD DESIGN WINDOWS FOR RESEARCH TRIALS

Parameter	Suggested research window	Rationale
Industrial binder total	10–30% dry soil mass	Captures low to moderate waste-binder replacement without excessive dilution
Bio-additive	0.25–1.5%	Covers low-dose bridging to upper workability limit
FA:GGBS ratio	75:25 to 25:75	Tests silica-rich vs calcium-rich blend response
Curing ages	0, 7, 28, 90 d	Separates immediate, medium, and longer-term reactions
Curing condition	Sealed, laboratory air, field-representative	Essential for distinguishing polymer and mineral mechanisms
Durability exposure	Soaking + repeated wet–dry cycles	Represents key service threat for expansive subgrades

XII. LIMITATIONS AND FUTURE RESEARCH

The principal limitation of current evidence is heterogeneity. “Expansive soil” encompasses a wide range of mineralogy, initial plasticity, clay fraction, salinity, and suction behavior. Similarly, fly ash and slag are not single materials; their chemistry depends on fuel, furnace, cooling, and grinding history. Biopolymers vary by purity, molecular weight, hydration procedure, and commercial formulation. Therefore, published optimum dosages should be treated as hypotheses for local validation, not universal specifications.

Long-term durability remains the most important unresolved issue for bio-based stabilization. Research should quantify retained strength after months of saturation, repeated wet–dry cycling, microbial exposure, elevated temperature, and freeze–thaw where relevant. Chemical analyses should examine whether industrial-waste alkalinity changes polymer structure or biodegradation rate. Conversely, polymer coatings may alter dissolution kinetics of FA/GGBS particles; this interaction should be studied using time-resolved pH, calorimetry, FTIR, SEM-EDS, and XRD.

Field-scale research should monitor moisture and deformation through seasonal cycles. Instrumented test sections can relate suction, volumetric water content, surface heave, and stiffness to laboratory metrics. Sustainability work should progress from qualitative scoring to project-specific life-cycle

assessment that includes local transport, preprocessing, activators, water demand, construction energy, maintenance, and end-of-life. Finally, standardized design procedures are required before hybrid industrial–bio stabilization can move from promising research to routine specification.

XIII. CONCLUSIONS

1. Industrial by-products can provide a credible low-virgin-binder route for improving expansive-soil plasticity, strength, bearing resistance, and swell behavior. Fly ash and GGBS are especially attractive because their silica–alumina–calcium chemistry supports pozzolanic, hydraulic, and geopolymeric bonding.
2. Bio-based additives provide a complementary mechanism based on hydrogel formation, hydrogen bonding, film formation, and pore filling. Guar gum, xanthan gum, and lignin have demonstrated meaningful improvements, but their response is strongly dependent on moisture state and curing.
3. Published evidence supports the hypothesis that a hybrid mineral–biopolymer matrix can combine durable inorganic cementation with low-dose organic bridging. The most promising research window is moderate industrial-binder content with a relatively small biopolymer dosage, followed by systematic curing and durability evaluation.
4. The optimum mixture should be selected using multiple criteria rather than maximum UCS alone. Swell reduction, soaked bearing response, wet–dry retention, constructability, circularity, carbon burden, and environmental safety must all be considered.
5. The proposed experimental framework provides a defensible route for producing project-specific data. A journal-quality study should report complete material characterization, exact mixing and curing protocols, standards-based testing, microstructural evidence, uncertainty/replicates, and clear separation between measured data and literature benchmarks.
6. Before large-scale field adoption, long-term wet durability, leachability of industrial residues, compatibility between polymer and mineral reactions, and field curing under seasonal moisture must be validated.

ACKNOWLEDGMENT

The author should replace this paragraph with project-specific acknowledgments, funding information, laboratory support, and material suppliers where applicable. No external funding or laboratory testing is claimed in the present literature-synthesis and proposed-framework manuscript.

REFERENCES

[1] J. D. Nelson and D. J. Miller, Expansive Soils: Problems and Practice in Foundation and Pavement Engineering. New York, NY, USA: Wiley, 1992.
[2] F. A. Gidebo, H. Yasuhara, and N. Kinoshita, “Stabilization of expansive soil with agricultural waste additives: a review,” International Journal of Geo-Engineering, vol. 14, art. no. 14, 2023, doi: 10.1186/s40703-023-00194-x.
[3] S. Ahmad, M. Shah Alam Ghazi, M. Syed, and M. A. Al-Osta, “Utilization of fly ash with and without secondary additives for stabilizing expansive soils: A review,” Results in Engineering, vol. 22, art. no. 102079, 2024, doi: 10.1016/j.rineng.2024.102079.
[4] J. Wei, J. Wei, Q. Huang, S. M. I. B. S. Zainal Abidin, and Z. Zou, “Mechanism and Engineering Characteristics of Expansive Soil Reinforced by Industrial Solid Waste: A Review,” Buildings, vol. 13, no. 4, art. no. 1001, 2023, doi: 10.3390/buildings13041001.
[5] A. K. Sharma and P. V. Sivapullaiah, “Ground granulated blast furnace slag amended fly ash as an expansive soil stabilizer,” Soils and Foundations, vol. 56, no. 2, pp. 205–212, 2016, doi: 10.1016/j.sandf.2016.02.004.
[6] E. R. Sujatha and S. Saisree, “Geotechnical behaviour of guar gum-treated soil,” Soils and Foundations, vol. 59, no. 6, pp. 2155–2166, 2019, doi: 10.1016/j.sandf.2019.11.012.
[7] I. Chang, M. Lee, A. T. P. Tran, S. Lee, Y.-M. Kwon, J. Im, and G.-C. Cho, “Review on biopolymer-based soil treatment (BPST) technology in geotechnical engineering practices,” Transportation Geotechnics, vol. 24, art. no. 100385, 2020, doi: 10.1016/j.trgeo.2020.100385.
[8] S. Kumar, B. D. Yadav, and R. Raj, “A review on the application of biopolymers (xanthan, agar and guar) for sustainable improvement of soil,” Discover Applied Sciences, vol. 6, art. no. 393, 2024, doi: 10.1007/s42452-024-06087-7.
[9] D. Sarker, O. S. Apu, N. Kumar, J. X. Wang, and J. G. Lynam, “Sustainable Lignin to Enhance Engineering Properties of Unsaturated Expansive Subgrade Soils,” Journal of Materials in Civil Engineering, vol. 35, no. 8, 2023, doi: 10.1061/JMCEE7.MTENG-15008.
[10] K. Chandraprakash, P. Kannan, V. Chandankeri, V. Kodli, V. U. Patil, M. Z. Kangda, and K. Taki, “Understanding the impact of laboratory and field curing conditions on the strength properties of black cotton soil treated with Xanthan Gum and Guar Gum Biopolymer,” Geomechanics and Geoengineering, vol. 20, no. 3, pp. 407–420, 2025, doi: 10.1080/17486025.2024.2413062.
[11] S. Kumar et al., “Fly ash-GGBS blended geopolymers for expansive soil stabilization: A critical review of evidence, limitations, and pathways to practice,” Next Materials, vol. 12, art. no. 102196, 2026, doi: 10.1016/j.nxmate.2026.102196.
[12] W. F. Kabeta and H. Lemma, “Modeling the application of steel slag in stabilizing expansive soil,” Modeling Earth Systems and Environment, vol. 9, pp. 4023–4030, 2023, doi: 10.1007/s40808-023-01734-1.
[13] L. Kanagarathinam, V. Govindaraj, V. Gokul, V. Muthukumaran, and Y. N. Sai, “Laboratory Evaluation of Stabilising Components for Effective Treatment of Expansive Soil,” Asian Journal of Water, Environment and Pollution, vol. 20, no. 4, pp. 87–91, 2023, doi: 10.3233/AJW230055.
[14] ASTM International, ASTM D4318-17, Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils. West Conshohocken, PA, USA: ASTM International, 2017.
[15] ASTM International, ASTM D698-12(2021), Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort. West Conshohocken, PA, USA: ASTM International, 2021.

[16] ASTM International, ASTM D2166/D2166M-24, Standard Test Method for Unconfined Compressive Strength of Cohesive Soil. West Conshohocken, PA, USA: ASTM International, 2024.
[17] ASTM International, ASTM D1883-21, Standard Test Method for California Bearing Ratio (CBR) of Laboratory-Compacted Soils. West Conshohocken, PA, USA: ASTM International, 2021.
[18] ASTM International, ASTM D4546-25, Standard Test Methods for One-Dimensional Swell or Collapse of Soils. West Conshohocken, PA, USA: ASTM International, 2025.
[19] N. Bansal, "Recycling and potential use of industrial cementitious waste in expansive soil stabilization: A review," Environmental Progress & Sustainable Energy, 2026, doi: 10.1002/ep.70535.
[20] C. Shao, M. Ma, X. Zhu, B. Xing, C. Zhang, D. Du, and R. Chi, "Phosphogypsum as an industrial byproduct: A critical review on environmental risks, remediation, and resource recovery-circular challenges," Process Safety and Environmental Protection, vol. 208, art. no. 108456, 2026, doi: 10.1016/j.psep.2026.108456.