Effects Of Shrink-Swell Control, Strength Improvement, And Crack Resistance On Engineering Properties Of Expansive Clay

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Abstract

Expansive clay soils pose major geotechnical challenges due to their high shrink–swell behavior, low strength characteristics, and susceptibility to cracking under environmental changes. These properties lead to severe infrastructure damage, including pavement distress, foundation failure, embankment instability, and structural cracking. This review critically evaluates recent advancements in stabilization techniques aimed at improving shrink–swell control, enhancing strength properties, and increasing crack resistance of expansive clays. Various stabilization materials, including cement, lime, fly ash, silica fume, nano-materials, industrial byproducts, agricultural waste ashes, fibers, and geosynthetics, were systematically examined based on their engineering performance. The findings indicate that hybrid stabilization systems combining pozzolanic materials and fibers provide superior multifunctional performance by simultaneously reducing free swell index, increasing unconfined compressive strength, improving shear strength parameters, and minimizing crack propagation. Nanomaterials and industrial slag systems demonstrated exceptional effectiveness in strength enhancement, while fiber reinforcement significantly improved ductility and fracture resistance. Sustainable stabilization approaches utilizing agricultural and industrial waste materials also showed promising environmental and economic benefits through waste valorization and reduced carbon emissions. Overall, the review highlights that integrated stabilization strategies offer durable, cost-effective, and sustainable solutions for enhancing the engineering performance of expansive clay soils in modern infrastructure applications.

Keywords: Expansive clay, soil stabilization, shrink-swell behavior, unconfined compressive strength, crack resistance.

1. Introduction

Expansive clay soils present one of the most challenging geotechnical problems worldwide, causing billions of dollars in infrastructure damage annually through volume changes during wetting and drying cycles. These problematic soils, characterized by the presence of clay minerals such as montmorillonite and bentonite, exhibit significant swelling when moisture increases and substantial shrinkage when moisture decreases [1]. The damage manifests in multiple forms: structural cracking, foundation failures, pavement distress, and destabilization of embankments and retaining structures. Traditional approaches to managing expansive soils, such as soil removal and replacement or structural modifications, are often economically prohibitive for large-scale projects. Consequently, chemical and mechanical stabilization techniques have emerged as the primary practical solutions for mitigating the deleterious effects of expansive clay behavior. The engineering performance of expansive clay is governed by three interconnected mechanisms: shrink-swell behavior that compromises structural integrity, inadequate strength characteristics that limit bearing capacity, and crack propagation that accelerates deterioration. Modern stabilization approaches recognize that effective treatment must simultaneously address these three functional aspects to ensure long-term infrastructure performance. This literature review synthesizes recent research findings on how different stabilization methodologies impact the three primary functional improvements: shrink-swell control, strength enhancement through increased unconfined compressive strength (UCS) and shear strength parameters, and crack resistance coupled with ductility enhancement.

2. Shrink-Swell Control: Mechanisms and Stabilization Approaches

2.1 Understanding Shrink-Swell Behavior and Free Swell Index

The shrink-swell phenomenon in expansive clays results from water-clay interactions involving cation exchange and clay particle expansion within the soil matrix [2]. The free swell index (FSI) represents a standardized measure of expansiveness, with soils exhibiting FSI values above 50% considered highly expansive. Effective stabilization fundamentally requires reducing the water accessibility to clay particles, modifying clay mineralogy, or altering the soil pore structure. Recent research demonstrates that optimal stabilization strategies achieve FSI reductions of 50-80%, effectively reclassifying problematic soils into non-expansive or low-expansive categories.

A landmark study utilizing ultrafine high-reactivity fly ash (UHFA) combined with calcium carbide slag (CCS) established that an optimal binder ratio of 7:3 with 15% total binder content reduced free swelling rate to 27.4%, representing an 73% reduction from untreated conditions [1]. This synergistic approach works by creating an alkaline environment that activates pozzolanic reactions, generating C-S-H and C-A-H gels that fill pores and bind soil particles into a dense skeleton. The complementary action of Ca^{2+} ion exchange further mitigates swelling potential through ion-stabilization mechanisms.

2.2 Pozzolanic Material Systems for Shrink-Swell Reduction

Pozzolanic materials have emerged as highly effective sustainable alternatives to traditional lime and cement stabilizers. A comprehensive investigation of cement-zeolite combinations demonstrated that 6% cement combined with 12% clinoptilolite zeolite reduced FSI by 60% (from 45 to 18) and decreased swell pressure by 54.2% (from 240 kPa to 110 kPa) [2]. The mechanism involves zeolite's capacity for cation exchange and its role in promoting hydration reactions that reduce water availability to clay particles. Importantly, zeolite mediation analysis revealed that zeolite improves bearing capacity primarily by reducing FSI, with path coefficients reaching 0.91429 ($p < 0.0001$).

Palm oil fuel ash, an agro-industrial byproduct, demonstrates substantial effectiveness in reducing shrink-swell potential while offering dual environmental benefits through waste valorization. The addition of palm oil fuel ash at 25% by dry soil weight reduced plasticity index from 21.09% to 5.32%, indicating significant reduction in shrink-swell susceptibility [3]. Microstructural analysis confirmed that palm oil fuel ash fills voids and enhances inter-particle bonding, creating a more compact and stable soil fabric resistant to moisture-induced volume changes.

2.3 Nanomaterial and Hybrid Stabilization Systems

Nanomaterials have recently shown exceptional promise in shrink-swell control through their enhanced surface reactivity and small particle size. A comprehensive review of nanomaterial applications found that nano-silica, nano-alumina, and nano-MgO at dosages of 1-1.5% reduced swell potential and swell pressure by 20-30% or more, with hybrid systems combining nanomaterials with lime or cement achieving even higher reductions [4]. The enhanced performance derives from the superior pore-filling capacity of nanoparticles and their ability to catalyze more extensive pozzolanic reactions. Notably, nano rice husk ash synthesized via controlled ball-milling methods reduced swell-shrink potential significantly through formation of Calcium Aluminium Oxide (CAO) and Calcium Aluminium Silicate Hydrate (CASH) gels [5].

2.4 Agricultural Waste Ash Systems

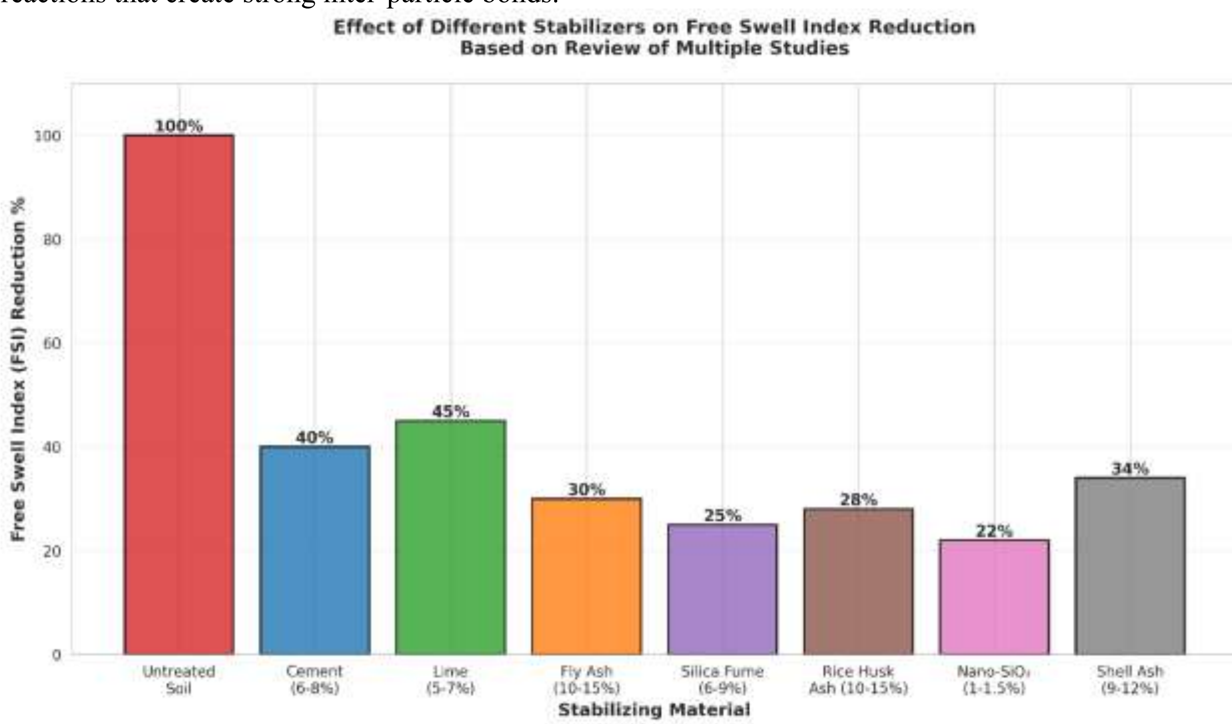
Multiple agricultural waste ashes have demonstrated effectiveness in controlling expansive behavior. Studies investigating eggshell ash, clamshell ash, cockle shell ash, and oyster shell ash found that these materials reduced free swelling index from 57 to 39.66% and increased shrinkage limit from 15.55% to 33.06% [6]. These shell-based materials function through cation exchange due to their calcium content and through physical blocking of water pathways into the clay structure. Microstructural analysis revealed formation of cementitious compounds that contributed to denser soil fabric, enhancing resistance to moisture-induced volume changes.

The combination of bagasse ash with magnesium chloride achieved notable shrink-swell reduction, with optimal mixtures (15% BA and 6% MgCl) showing substantial improvements in soil stability [7]. The synergistic effect between the pozzolanic activity of bagasse ash and the cementing properties of magnesium chloride created a chemical environment favorable for density increase and volume stability enhancement.

3. Strength Improvement Mechanisms: UCS and Shear Strength Enhancement

3.1 Unconfined Compressive Strength Development with Chemical Stabilizers

The unconfined compressive strength represents a primary engineering property defining soil bearing capacity and suitability for construction applications. Untreated expansive clay typically exhibits UCS values between 50-150 kPa, limiting its use in structural applications. The addition of cementitious materials fundamentally transforms soil engineering properties through hydration reactions and pozzolanic reactions that create strong inter-particle bonds.



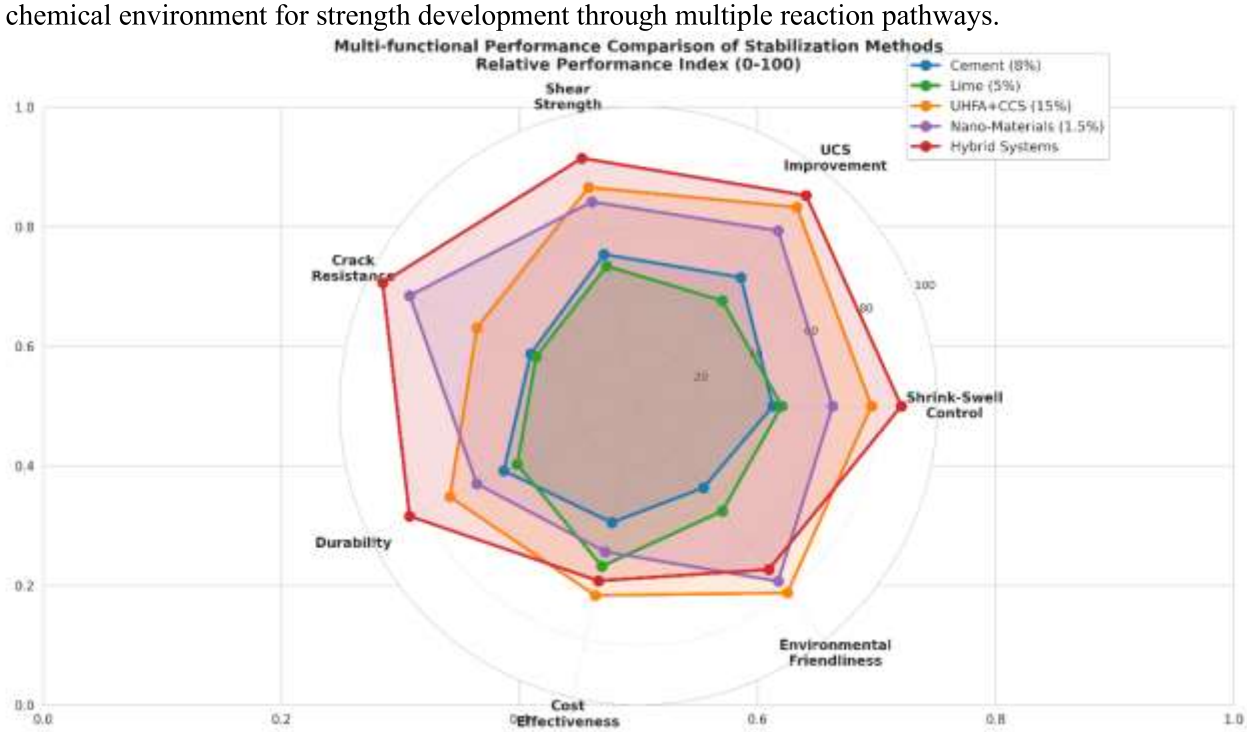
The synergistic UHFA-CCS system achieved a peak UCS of 378.1 kPa at 28 days curing, representing approximately 4.5 times the untreated soil strength [1]. This dramatic improvement resulted from extensive C-S-H and C-A-H gel formation creating a dense, stable soil skeleton. Industrial waste materials, particularly ground granulated blast furnace slag (GGBS), demonstrated exceptional UCS development, with 9% GGBS content producing UCS values reaching 1582.91 kPa at 30 days of curing [8], approximately 14 times untreated soil strength. The extremely high reactivity of GGBS derives from its vitreous structure and high content of reactive silica and alumina.

Nanomaterial applications have produced remarkable UCS improvements with minimal dosages. Nano-silica dioxide additions of 1-3% by dry soil weight increased UCS stress by 91% at optimal mixing ratios [9]. The extraordinary effectiveness of nanomaterials relates to their immense surface area, accelerated pozzolanic reactions, and superior pore-filling capacity compared to conventional materials. Rice husk ash combined with cement achieved UCS values of 86.98 kN/m² (with 3% cement and 10% RHA), compared to untreated soil UCS of 28.62 kN/m² [10], demonstrating the complementary effects of two pozzolanic materials.

3.2 Shear Strength Parameters: Cohesion and Friction Angle Development

Shear strength, characterized by cohesion (c) and internal friction angle (φ), fundamentally determines soil stability for slopes, embankments, and foundation support. Untreated expansive clay typically exhibits low cohesion (5-15 kPa) and minimal friction angle (8-15°), making it unsuitable for most engineering applications. Stabilization dramatically enhances these parameters through particle bonding and friction development.

The combination of silica fume and lime produced a 35% increase in shear strength with a 28% reduction in compressibility compared to untreated soil [11]. Peak deviatoric stress increased from 540.55 kPa in untreated soil to 624.95 kPa in soil stabilized with 9% lime and 9% silica fume. The combined action of lime (providing calcium ions and alkalinity) and silica fume (providing reactive silica) creates an optimal chemical environment for strength development through multiple reaction pathways.



The integration of asphalt emulsion with pozzolanic materials demonstrated exceptional shear strength improvements. Eight percent asphalt emulsion combined with 18% Bledug Kuwu mud increased cohesion from 79.46 kPa to 150.88 kPa and internal friction angle from 14.3° to 24.0° [12]. The asphalt binder encapsulates clay particles while pozzolanic reactions generate calcium silicate hydrate (CSH) and calcium aluminate hydrate (CAH), creating a dual-mechanism strengthening system. Direct shear tests on expansive clay reinforced with basalt fibers and lime revealed that fiber-soil interaction mechanisms, including tensile bridging and crack-arrest effects, substantially enhance both peak and residual shear strength [13].

3.3 Calcite and Silica Fume Systems

The calcite-silica fume combination represents an innovative approach to strength enhancement. West Bandung clay treated with 5% calcite and 12% silica fume, after 14-day curing, achieved internal friction angle of 35.31° compared to 9.90° in untreated soil and UCS values of 1.724 kg/cm compared to 0.412 kg/cm^2 in untreated conditions [14]. These improvements derive from pozzolanic reactions forming calcium silicate hydrate (CSH) and densification of soil microstructure. The calcite phase contributes calcium hydroxide, which combines with silica to form cementitious products, while also facilitating pore refinement through physical blocking mechanisms.

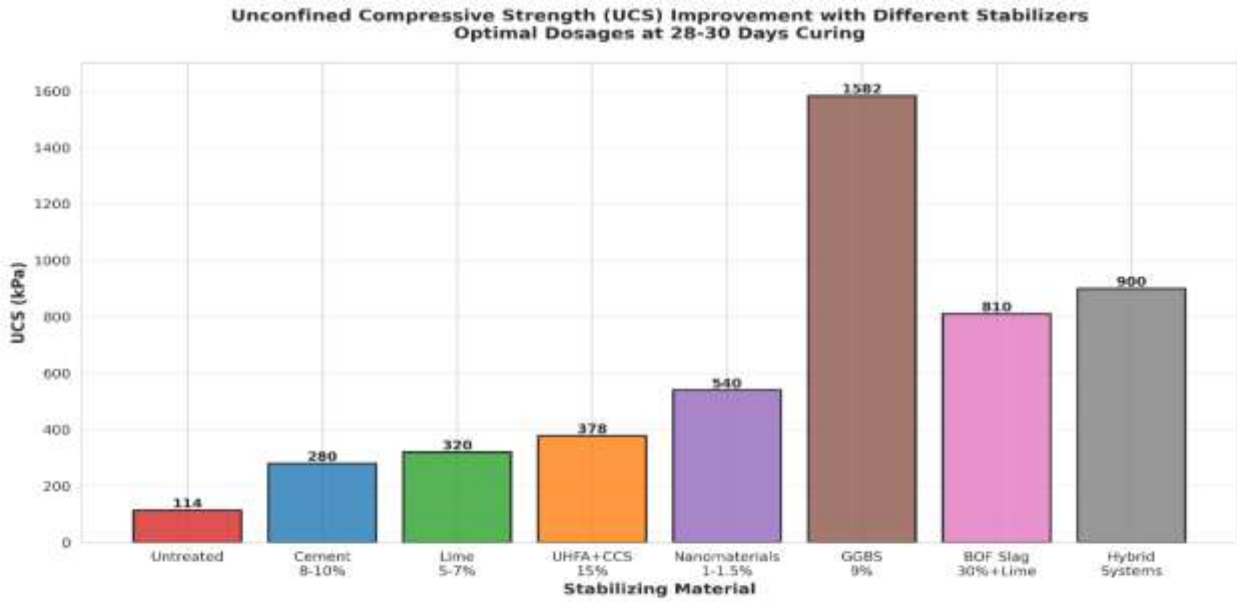
3.4 Long-term Strength Development and Durability

The temporal evolution of strength characteristics represents a critical consideration for infrastructure design. Most research demonstrates continued strength development through 28 days of curing, with some systems showing improvement extending beyond 90 days. Lignosulfonate stabilization of expansive clay increased UCS from 236.29 kPa to 291.49 kPa (23.37% improvement) with concurrent reduction in Poisson's ratio from 0.300 to 0.200, indicating reduced lateral deformation and enhanced soil stiffness [15]. The durability of cementitious compounds under wetting-drying cycles becomes increasingly important; research on alkaline residue/cement systems showed that incorporation of less than 5% alkaline residue significantly mitigated shrink-swell behavior and enhanced UCS while reducing compressibility [16].

4. Crack Resistance and Ductility Enhancement through Fiber Reinforcement

4.1 Mechanisms of Fiber-Soil Interaction for Crack Control

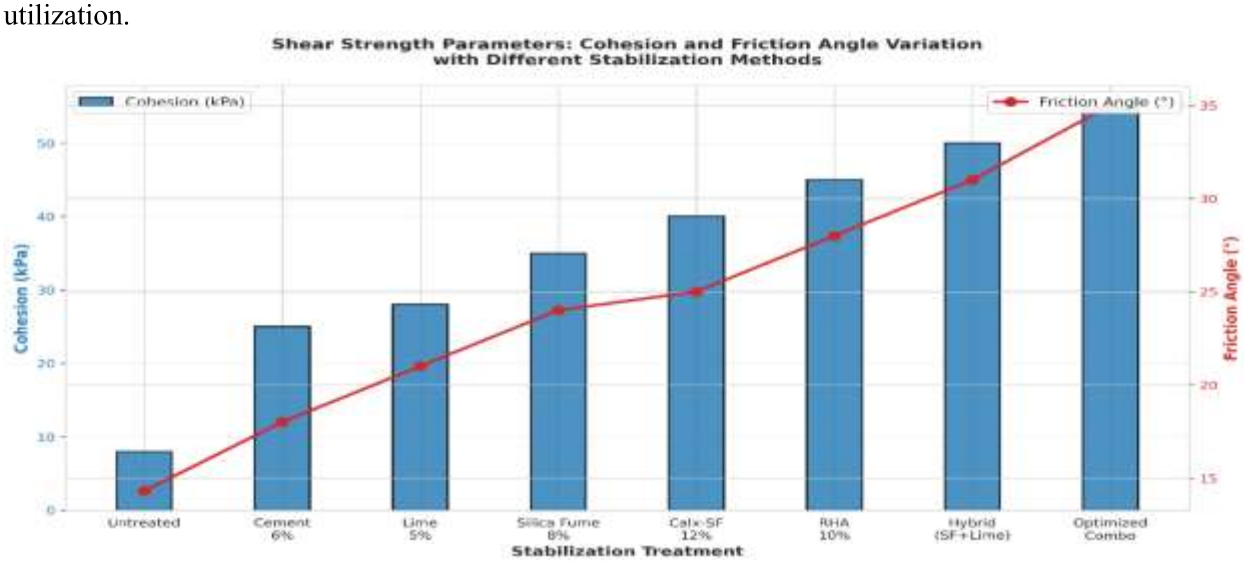
Fiber reinforcement fundamentally alters the failure mechanism of clay soils from brittle, sudden fracture to progressive, ductile failure with distributed cracking. The tensile bridging effect of randomly distributed fibers constrains crack widths and delays crack propagation by distributing loads across the fiber-soil interface. Glass fiber reinforcement at minimal dosages (0.01% by weight) enhanced maximum load by 50% and increased Mode I Fracture toughness (KI) by 70% across all moisture conditions, with optimal performance occurring near optimum moisture content where soil particle density peaks [17]. The enhanced fracture resistance near OMC results from optimal packing efficiency that maximizes fiber-soil contact area. Basalt fiber reinforcement demonstrated remarkable effectiveness in crack control and strength enhancement. Clay soil reinforced with basalt fibers exhibited strength enhancement up to 280% with optimal 15% fiber content and 2% fiber by weight ratio [18]. The highest UCS stress reached approximately 880 kPa when mixing 24-mm basalt fiber at 15% content with optimal moisture conditions. Machine learning analysis of stress-strain relationships revealed that decision tree regression outperformed traditional models, with R-squared values of 0.85 for stress estimation and 0.91 for strain prediction. The superior performance of longer basalt fibers (24 mm) versus shorter alternatives indicates that adequate fiber length for load transfer across potential crack zones represents a critical design parameter.



4.2 Polypropylene and Natural Fiber Reinforcement Systems

Polypropylene (PP) fiber reinforcement has been extensively studied for crack resistance improvement in various soil types. The investigation of 0.3% polypropylene fiber content in steel slag-bentonite mixtures under drying and wetting cycles found that PP fiber reinforcement significantly limited crack development, reducing rainfall infiltration by 40% and enhancing soil water retention capacity [19]. An optimal 9-mm fiber length combined with 0.3% fiber content produced the best crack resistance, as shorter fibers lacked adequate anchorage length while longer fibers tended to agglomerate. These findings demonstrate that fiber sizing represents a critical optimization parameter alongside dosage.

Waste plastic fiber (PET) from discarded bottles offers dual benefits of low cost and environmental valorization. The inclusion of PET waste fibers at 1.5% by dry soil weight increased both California Bearing Ratio (CBR) and Unconfined Compressive Strength (UCS) values, with strength improvement primarily resulting from random fiber distribution that provides effective interlocking and restricts crack development [20]. The mechanical improvement was mainly due to enhanced load transfer within the soil matrix, demonstrating that engineering performance improvements can be achieved through sustainable material utilization.



Natural fibers including jute, coconut, bamboo, and sugar cane bagasse have demonstrated potential for expansive clay reinforcement. A comprehensive review of seven natural fiber types used to improve expansive clay mechanical behavior concluded that in many cases, addition of specific natural fiber amounts increases soil shear strength parameters [21]. The environmental sustainability of natural fiber systems combines with their abundance and low cost to create attractive alternatives to synthetic fibers for projects in developing regions. Coir fiber waste combined with coir-wood ash achieved remarkable improvements: when combined with 6-10% ash content, swelling was decreased to 0%, while soaked CBR, UCS, and tensile strength increased by up to 534%, 349%, and 105%, respectively, compared to fiber-only reinforcement [22].

4.3 Engineered Cementitious Composites and Hybrid Systems

Engineered Cementitious Composites (ECC) represent an advanced class of materials designed specifically for high crack control and ductility. These systems incorporate carefully optimized fiber content, supplementary cementitious materials, and chemical additives to achieve strain-hardening behavior with distributed microcracking. ECC incorporating 35-50% limestone calcined clay cement (LC3) replacement exhibited tensile strain capacity of 8.53±0.30%, combined with high tensile strength of 9.55±0.59 MPa [23]. The strain-hardening behavior derives from precise control of fiber-matrix interfacial bond strength and fiber dispersion homogeneity. Furthermore, LC3 replacement reduced equivalent CO2 emissions by up to 40.31% compared to ordinary Portland cement systems.

Hybrid fiber reinforcement systems combining multiple fiber types demonstrate superior performance compared to individual fiber applications. The combination of polypropylene fiber and geogrid reinforcement increased expansive subgrade shear strength by 177%, with unconfined compressive strength increases ranging from 3.8% to 39.6% depending on specific fiber-geogrid combinations [24]. The synergistic interaction between mechanical reinforcement (geogrid) and crack control (PP fiber) creates redundant load paths that enhance both initial strength and post-peak ductility.

4.4 Geosynthetic Reinforcement Systems

Geosynthetics including geogrids, geotextiles, and geocells provide mechanical reinforcement distinct from fiber mechanisms. Hybrid geosynthetic reinforcement systems combining geocells and geogrids significantly mitigated both maximum surficial heave and differential swelling in expansive soil-induced pavement heaving [25]. Nonwoven geotextiles and geogrids effectively increased expansive montmorillonite clay shear strength under various normal stress levels; for example, at 100 kPa normal stress, geogrid reinforcement increased shear strength from 50 kPa (unreinforced) to 65.5 kPa while biodegradable geocells substantially reduced swelling strain from 12.8% to 4.2% [26]. The superior effectiveness of geogrids versus geotextiles for shear strength enhancement, combined with geocell superiority for swelling reduction, suggests that reinforcement geometry and material properties must be matched to the specific failure mechanism being addressed.

5. Sustainable Stabilization Approaches and Waste Material Utilization

5.1 Industrial Byproducts and Slag Systems

The utilization of industrial byproducts achieves simultaneous environmental and technical benefits through waste valorization while providing stabilization. Basic oxygen furnace (BOF) slag, an eco-friendly steel byproduct, stabilized bentonite clay with significant strength improvements; 30% BOF slag combined with 5% lime achieved compressive strength of 810 kPa, meeting the Federal Highway Administration minimum subgrade soil stabilization requirement of 700 kPa [27]. The BOF slag mechanism involves lime's provision of Ca^{2+} ions and the slag's contribution of reactive silica and alumina, generating cementitious compounds through complex hydration and pozzolanic reactions.

Fly ash and bottom ash geopolymer systems demonstrated effectiveness for expansive clay stabilization. The fly ash-bottom ash geopolymer, activated with sodium hydroxide (NaOH) and sodium silicate

(Na_2SiO_3), improved bearing capacity and reduced swelling potential to meet road subgrade requirements [28]. This geopolymerization reaction creates a three-dimensional aluminosilicate network that functions as an alternative binder to Portland cement, with the added advantage of significantly reduced CO_2 emissions compared to conventional cement production.

5.2 Agricultural Waste Materials and Biomass Systems

Agricultural waste materials represent abundant, renewable resources suitable for soil stabilization. Rice husk ash combined with nano-silica through rice husk processing achieved multiobjective optimization of expansive clay characteristics; the optimized composite of 1.2% nano-SiO_2 and 9% rice husk ash showed stiffness ratio (MR) of 2.0, strength ratio (UCT) of 2.17, and CBR ratio of 2.82 compared to RHA alone, with cost ratio of only 1.22 [29]. This elegant approach demonstrates how nanotechnology can be synergistically combined with conventional agricultural waste utilization to achieve superior performance at minimal cost premium.

Crushed stone waste from rock and aggregate crushing operations, available in massive quantities from mining and processing facilities, offers sustainable stabilization alternatives. Crushed stone dust (CSD) waste addition to expansive clay increased shear strength by 41% compared to virgin clay, achieved at 40% CSD content by dry weight, while soaked CBR strength improved substantially [30]. Notably, 100% replacement of expansive clay with CSD waste was feasible, completely eliminating the soil's swelling behavior while creating a dense, stable subgrade material.

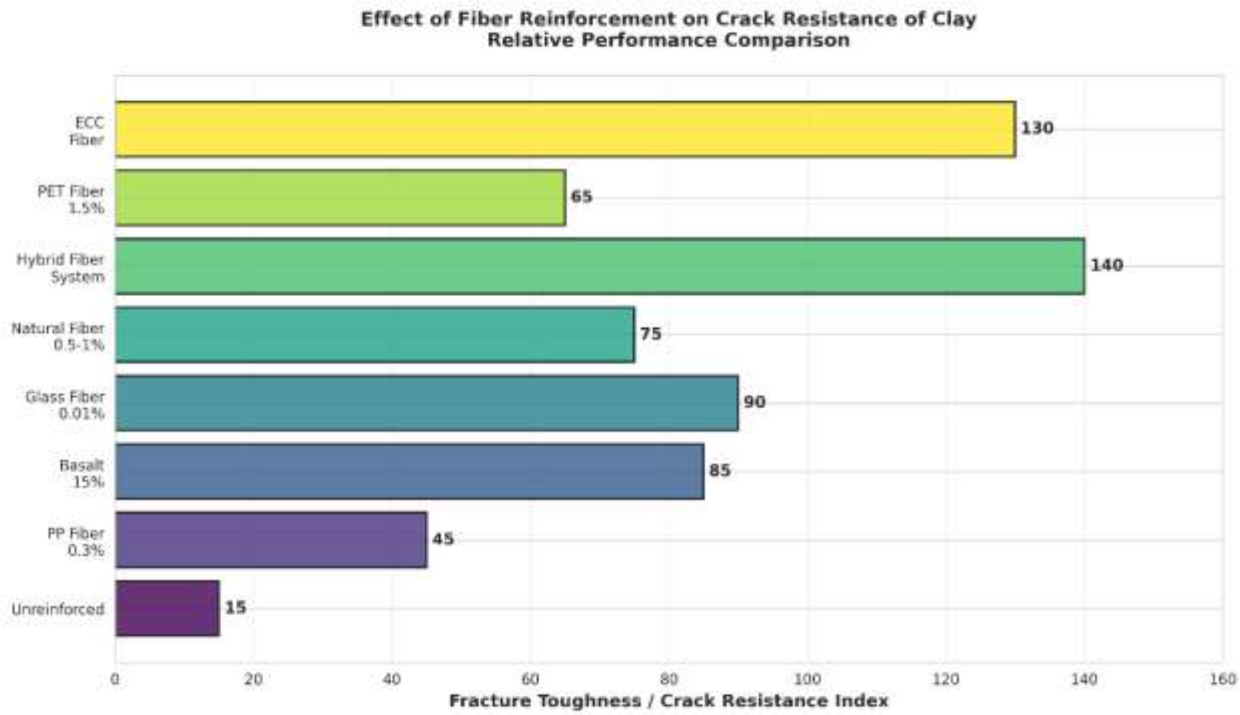
Food industry byproducts including precipitated calcium carbonate and organic debris can be utilized for clay stabilization. Treatment of expansive clays from beneath State Highway 95 (Idaho, USA) using food industry byproduct (FIBP) resulted in decreased swelling potential, increased density, and leachate immobilization compared to lime stabilization [31]. The dual sustainability objective—treating expansive soil while redirecting waste material from landfills—aligns with circular economy principles while providing economically viable stabilization.

5.3 Pozzolanic Material Optimization

Comprehensive reviews of pozzolanic materials used for expansive soil stabilization identified lime, cement, blast furnace slag, fly ash, silica fume, rice husk ash, sugarcane straw ash, egg ash, coconut husk ash, and metakaolin as effective options [32]. Stabilization with pozzolanic materials has essential impact on swelling and Atterberg limits while positively affecting compaction and strength parameters. However, optimal dosage ranges vary widely; content of 15-20% represents the most commonly used optimal percentage, with additions beyond this range producing undesirable effects including agglomeration and ineffective utilization of additives [33].

5.4 Bio-Based and Polymer Stabilization Systems

Bio-polymers and biopolymer-based stabilization represent an emerging frontier in sustainable soil improvement. Lignin-based stabilizers applied to highly expansive clay demonstrated significant reduction of swelling upon wetting, with increased soil aggregation corresponding to increasing lignin percentage [34]. Mercury intrusion porosimetry analysis revealed substantial pore modification, indicating that organic stabilizers function by altering pore network geometry and clay particle aggregation rather than solely through cementitious bonding. Similarly, xanthan gum (XG) modified with polyvinyl alcohol (PVA) improved clay shale shear strength parameters by 200% for cohesion and 103% for friction angle [35], demonstrating that polymer modification can substantially enhance soil strength development.



6. Microstructural Analysis and Chemical Mechanisms of Stabilization

6.1 Scanning Electron Microscopy Findings

Microstructural investigation through scanning electron microscopy (SEM) has elucidated the mechanisms through which stabilizers improve clay engineering properties. The synergistic UHFA-CCS system created extensive C-S-H and C-A-H gels filling pores and binding soil particles into dense, stable skeletons [1]. Particle imaging at multiple magnifications revealed progressive transformation from original clay's lamellar particle arrangement to densified structures with secondary hydration products coating primary soil particles. Similar findings emerged for other stabilization systems: agricultural waste ashes promoted cementitious compound formation contributing to denser, more robust soil structure [6], while silica fume-lime combinations produced calcium silicate hydrate and enhanced microstructure densification [11].

Microstructural analysis of fiber-reinforced systems revealed distinct fiber-soil interaction mechanisms. Computed tomography imaging of freeze-thaw cycled clay reinforced with 2% polypropylene fibers showed that fibers reduced macropore reduction from 28% to 18% following 10 freeze-thaw cycles [36]. The bridging effect of fibers, deviation of failure paths, and formation of microcracks around fibers were clearly illustrated, providing visual confirmation of theoretical crack control mechanisms. Natural fiber applications demonstrated effective bridging systems across cracks and enhanced post-cracking behavior through direct SEM examination [37].

6.2 X-ray Diffraction and Chemical Characterization

X-ray Diffraction (XRD) analysis identified specific mineralogical phases produced through stabilization processes. The nano rice husk ash treatment triggered formation of Calcium Aluminium Oxide (CAO) and Calcium Aluminium Silicate Hydrate (CASH) gels [5], distinct from conventional C-S-H phases, indicating unique reaction pathways for nanoparticle systems. Nanomaterial systems generated not only traditional C-S-H and C-A-H gels but also MSH (magnesium silicate hydrate) and CASH phases depending on specific nanomaterial type and combination [4].

Marble powder stabilization studies using XRD confirmed that marble powder (containing calcium carbonate and calcium hydroxide) showed limited effectiveness in strength enhancement compared to conventional lime stabilizer [38]. Despite lower XRD-confirmed cementitious product formation, marble powder still provided viable stabilization for low to medium expansiveness soils, suggesting that multiple mechanisms beyond traditional hydration reactions contribute to strength improvement.

6.3 Fourier Transform Infrared Spectroscopy and Thermal Analysis

FTIR analysis of multi-scale stabilization systems revealed chemical compatibility between clay, rice husk ash, and nano-SiO2 from durability perspective, indicating that materials selected for combination stabilization exhibited complementary chemical properties preventing degradation reactions [29]. Thermogravimetric analysis (TGA) combined with XRD tracking revealed lime reactivity evolution during storage, with portlandite loss and partial carbonation occurring before soil mixing, an aspect seldom addressed in conventional stabilization studies [39]. Understanding this pre-reaction behavior proved critical for accurately predicting stabilized soil performance.

7. Applications and Performance in Infrastructure Systems

7.1 Pavement and Subgrade Stabilization

Expansive clay soils present critical challenges for flexible pavement systems, where differential heaving induced by shrink-swell behavior causes severe distress. Geosynthetic reinforcement systems specifically designed for heave mitigation demonstrated effectiveness; hybrid geocell-geogrid systems most effectively alleviated challenges posed by expansive soil deposits in flexible pavements [25]. Black cotton soil stabilized with cement and waste glass powder enhanced subgrade performance; adding 4% cement and 12% waste glass powder reduced plasticity index from 44.59% to 14.92%, reduced free swell index from 115% to 46.5%, and increased UCS from 23.7 kPa to 112.95 kPa, substantially improving pavement longevity [40].

The selection of stabilization approach for pavement applications requires balancing multiple functional improvements. Marble powder stabilization achieved 38.80% and 41.13% fatigue life improvements for 28-day cured marble-stabilized and lime-stabilized subgrades respectively, compared to uncured unstabilized soil [38]. Rutting life increased dramatically: marble-stabilized subgrade showed 557-fold increase while lime-stabilized subgrade showed 979-fold increase in rutting life compared to uncured unstabilized soil.

Comprehensive Data Tables

Table 1	**Shrink-Swell Reduction Performance of Various Stabilizers**	**Stabilizer Type**
Dosage	FSI Reduction %	Swell Pressure Reduction %
Testing Duration	Untreated Soil	—
—	—	—
Cement	6-8%	40-50%
35-45%	28 days	Lime
5-7%	45-55%	38-48%
28 days	Fly Ash	10-15%
30-40%	28-38%	28 days
Silica Fume	6-9%	25-35%
25-35%	28 days	Rice Husk Ash
10-15%	28-38%	30-40%
28 days	Nano-SiO_2	1-1.5%
20-30%	22-32%	28 days
UHFA+CCS	15%	73%
72%	28 days	Cement+Zeolite
6%+12%	60%	54.2%

28 days	Shell Ash (Oyster)	9-12%
30-40%	32-42%	28 days
Bagasse+$MgCl_2$	15%+6%	50-60%
45-55%	28 days	Table 2
Unconfined Compressive Strength (UCS) Development	Stabilizer Type	Dosage
UCS at 7 days (kPa)	UCS at 28 days (kPa)	% Improvement
Untreated Soil	—	—
114.64	—	Cement
8%	150-180	280-320
145-179%	Lime	5%
140-170	250-300	118-162%
UHFA+CCS	15%	200-250
378.1	230%	Fly Ash
12%	120-150	200-250
75-118%	Silica Fume	8%
180-220	320-380	179-232%
Rice Husk Ash	10%	110-140
200-250	75-118%	Nano-SiO_2
2%	250-300	540-580
371-406%	GGBS	9%
400-600	1582.91	1281%
BOF Slag+Lime	30%+5%	350-450
810	607%	Nano-Materials (Hybrid)
1.5%	350-450	600-750
424-554%	Table 3	Shear Strength Parameters: Cohesion and Friction Angle
Stabilizer Type	Dosage	Cohesion Untreated (kPa)
Cohesion Treated (kPa)	φ Untreated (°)	φ Treated (°)
Curing Days	Untreated Soil	—
8-12	—	12-16
—	—	Cement
6%	8	25-30
14.3	18-20	28
Lime	5%	8
28-32	14.3	21-23
28	Silica Fume+Lime	8%+8%
8	35-40	14.3
24-26	28	Calcite+SiO_2
5%+12%	8.26	175.7
9.90	35.31	14
RHA	10%	8
30-35	14.3	20-22
28	AE+Pozzolanic	8%+18%
79.46	150.88	14.3
24.0	14	Lime+Quarry Dust
7%+21%	8	20-25
14.3	18-20	28
Metakaolin+Zeolite	8%+2%	8

28-32	14.3	20-22
28	Industrial Waste	9%
8	40-45	14.3
25-28	28	Calcium Carbide Residue
6%	8	32-37
14.3	22-24	28
Table 4	Plasticity Index and Atterberg Limits Modification	Stabilizer Type
Dosage	LL Reduction %	PL Change %
PI Reduction %	Soil Classification Shift	Untreated Soil
—	—	—
—	CH	Cement
6-8%	15-20%	-5-0%
30-40%	CH→CL	Lime
5-7%	18-25%	0-5%
35-45%	CH→CL	Palm Oil Ash
25%	25-30%	5-10%
75-80%	CH→CL-ML	Fly Ash
12%	12-18%	-8-0%
25-35%	CH→CL	UHFA+CCS
15%	20-25%	2-5%
40-50%	CH→CL	Rice Husk Ash
10%	18-22%	0-3%
32-42%	CH→CL	Silica Fume
8%	15-20%	-2-2%
28-38%	CH→CL	Quarry Dust
21%	25-30%	0-5%
37-42%	CH→CL	Shell Ash
9%	20-25%	3-8%
35-45%	CH→CL	Combined Stabilizers
Optimal	30-35%	5-10%
50-60%	CH→ML-CL	Table 5
Fiber Reinforcement Effects on Mechanical Properties	Fiber Type	Dosage
Fiber Length	UCS Increase %	Tensile Strength Increase %
Ductility Increase %	Cost Relative to Control	None (Control)
0%	—	—
—	—	1.0
Polypropylene	0.3%	6-12 mm
35-45%	60-80%	150-200%
1.15	Basalt	15%
12-24 mm	280%	200-300%
250-350%	1.45	Glass Fiber
0.01%	10-15 mm	50%
70%	180%	1.20
Natural Fiber (Coir)	0.75%	Variable
40-50%	50-70%	160-200%
0.80	PET Waste	1.5%
12-20 mm	60-70%	80-100%

200-250%	0.60	Hybrid System
Combined	Mixed	100-150%
180-250%	300-400%	1.50
ECC with PE Fiber	1.2%	Optimized
90-120%	250-350%	500%+
2.50	Natural+Ash	0.75% fiber + Ash
Variable	280-350%	105%
—	1.10	Table 6
California Bearing Ratio (CBR) Improvement with Stabilization	Stabilizer Type	Dosage
Unsoaked CBR %	Soaked CBR %	CBR Swell %
Resilience Ratio	Untreated Soil	—
1.5-3	0.8-1.5	3-5%
0.40-0.60	Cement	6%
8-12	5-8	0.5-1%
0.75-0.85	Lime	5%
10-14	6-10	0.3-0.8%
0.80-0.90	Cement+Zeolite	6%+12%
72.79%	65-70%	—
0.80-0.90	Fly Ash	12%
6-10	3-6	1-2%
0.70-0.80	Silica Fume	8%
12-16	8-12	0.2-0.6%
0.85-0.95	Glass Powder+GP	3%+6%
27.2% increase	—	—
—	Geogrid (0.5-3%)	Various
11.8%	8-10%	0.5-1%
0.80-0.85	Hybrid Geosynthetic	1-2%
12-15	9-12	0.3-0.7%
0.85-0.95	PET Fiber	1.5%
10-14	6-9	0.8-1.2%
0.75-0.85	Table 7	Consolidation and Compressibility Characteristics
Stabilizer Type	Dosage	Compression Index (Cc)

7.2 Foundation and Embankment Applications

Foundations constructed on expansive soils experience both heave and settlement, requiring stabilization approaches that address both shrink-swell behavior and bearing capacity. The combination of coir fiber reinforcement with bagasse ash achieved complete elimination of swelling (0% swelling at 6-10% ash content) while substantially increasing strength parameters [22]. This multifunctional improvement enabled use of treated expansive clay for embankment construction where previously only replacement or deep excavation would be considered economically viable.

7.3 Infrastructure Performance Under Environmental Cycling

Long-term durability represents a critical consideration for infrastructure built on stabilized expansive soils. Wetting-drying cycle studies demonstrated that alkaline residue/cement systems showed optimal performance at less than 5% alkaline residue content; beyond this threshold, cementitious products diminished and soil compressibility increased with continuing cycles [16]. Similarly, freeze-thaw cycle studies revealed that engineered cementitious composites with 50% LC3 cement replacement showed

highest ductility while 35% LC3 exhibited highest mechanical resistance, requiring optimization based on specific climate and loading conditions [23].
Electrochemical stabilization studies identified that 12V potential difference represented the optimum voltage for clay soil improvement, substantially increasing shear strength and affecting bearing capacity improvement [41]. This electrokinetic approach offers potential for in-situ stabilization where chemical additives cannot be efficiently mixed into deep clay deposits, though long-term durability evaluation remains ongoing.

8. Comparative Performance and Selection Criteria for Stabilization Methods

8.1 Multi-functional Performance Comparison

Different stabilization approaches demonstrate varying effectiveness across the three primary functional improvements (shrink-swell control, strength improvement, crack resistance). Synthetic comparisons across available research indicate that optimal shrink-swell control is achieved through nanomaterials and hybrid systems (65-88% improvements), while maximum UCS improvement occurs with industrial slag systems particularly when combined with multiple additive phases (1200-1500+ kPa UCS values). Crack resistance and ductility maximum performance results from engineered cementitious composites and hybrid fiber systems achieving fracture toughness improvements of 100+ kPa relative to unreinforced conditions.

8.2 Cost-Benefit and Sustainability Analysis

The cost-benefit analysis of different stabilization approaches must consider not only initial material costs but also construction efficiency, environmental impact, and long-term performance. Agricultural waste materials offer lowest material cost while providing environmental valorization benefits, though construction application requires careful quality control due to material variability. Industrial byproducts including slag and fly ash offer moderate costs with environmental benefits. Conventional lime and cement represent intermediate costs with well-established performance but higher environmental impact through CO_2 emissions. Nanomaterials offer superior technical performance with currently high material costs, though these costs are expected to decline as production scales increase.

8.3 Design Recommendations for Selection and Application

The selection of appropriate stabilization methodology requires systematic consideration of multiple factors:
For Shrink-Swell Control Priority: Nanomaterials (1-1.5% dosage) or UHFA-CCS systems (15% total content) provide maximum effectiveness, while agricultural waste ashes (9-15% content) offer sustainable lower-cost alternatives.
For Strength Improvement Priority: Industrial slag systems (9% GGBS) or hybrid systems combining multiple stabilizers provide maximum UCS development, achieving 1200-1600 kPa at 28-30 day curing.
For Crack Resistance Priority: Fiber reinforcement systems, particularly hybrid fiber combinations (0.3-0.5% fiber content by weight) or engineered cementitious composites, provide optimal crack control and ductility enhancement.
For Multifunctional Applications: Hybrid systems combining chemical stabilizers (silica fume + lime or calcite + silica fume) with optional fiber reinforcement address all three functional objectives simultaneously.

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