SUSTAINABLE SOIL STABILIZATION USING LIME AND POLYPROPYLENE FIBER REINFORCEMENT: AN EXPERIMENTAL INVESTIGATION

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Abstract

Expansive clayey soils, characterized by high plasticity, low bearing capacity, and pronounced volumetric swell-shrink behavior, present a persistent geotechnical challenge for foundations, embankments, and pavement subgrades in arid and semi-arid regions. Lime stabilization is a well-established chemical treatment for reducing plasticity and swelling, but lime-treated soils remain relatively brittle and can develop shrinkage cracks that compromise long-term durability. This paper presents LPFS (Lime–Polypropylene Fiber Stabilization), a combined experimental investigation into the geotechnical behavior of an expansive clayey soil treated with hydrated lime and discrete polypropylene (PP) fiber reinforcement. Soil specimens were prepared at lime contents of 0, 2, 4, 6, and 8% by dry weight to identify the optimum lime dosage, after which polypropylene fiber was incorporated at 0, 0.3, 0.6, 0.9, and 1.2% by dry weight at the optimum lime content to identify the optimum fiber dosage. Unconfined compressive strength (UCS), soaked California Bearing Ratio (CBR), free swell index, and wet-dry durability tests were carried out on treated and untreated specimens cured for 7, 28, and 90 days. The results show that 6% lime content produced the highest practical gain in 28-day UCS, beyond which additional lime yielded only marginal improvement. At this optimum lime content, the addition of 0.9% polypropylene fiber increased the 28-day UCS by approximately 29% relative to the lime-only mix and by close to 500% relative to the untreated soil, while increasing the failure strain at peak stress by more than three and a half times, indicating a marked improvement in post-peak ductility. The combined lime-fiber treatment increased the soaked CBR from 2.1% for the untreated soil to 13.8%, and reduced the free swell index from 92% to 24%. Under twelve cycles of wet-dry durability testing, the lime-fiber specimens retained substantially more mass than the lime-only specimens, confirming improved resistance to moisture-induced deterioration. The results demonstrate that combined lime and polypropylene fiber treatment offers a sustainable, low-cement-content stabilization strategy that simultaneously improves strength, bearing capacity, volumetric stability, ductility, and durability of expansive subgrade soils.

Keywords: Expansive Soil; Lime Stabilization; Polypropylene Fiber Reinforcement; Unconfined Compressive Strength; California Bearing Ratio; Free Swell Index; Durability; Sustainable Ground Improvement

1 Introduction

Expansive clayey soils, commonly referred to as black cotton soils in the Indian subcontinent and as high-plasticity or reactive clays elsewhere, cover extensive tracts of semi-arid and sub-humid regions worldwide. These soils are characterized by a high content of montmorillonitic clay minerals, which give rise to substantial volume change on wetting and drying, low unconfined compressive strength, low bearing capacity, and poor resistance to shear deformation. When used directly as a foundation or pavement subgrade material, expansive soils are responsible for a large proportion of structural distress in low-rise buildings, canal linings, and highway pavements, manifesting as differential heave, cracking, and premature pavement failure.

Chemical stabilization with hydrated lime is among the most widely used and economical methods of improving the engineering behavior of expansive soils. The pozzolanic reaction between lime, water, and the reactive clay minerals produces cementitious calcium-silicate and calcium-aluminate hydrates that reduce plasticity, lower the swelling potential, and increase strength and stiffness over time. However, lime-stabilized soils, while stronger and less plastic than the untreated material, tend to behave in a relatively brittle manner, losing load-carrying capacity abruptly once the peak strength is exceeded, and remain susceptible to shrinkage cracking during drying, which can create preferential pathways for moisture ingress and reduce long-term durability.

Discrete fiber reinforcement, using materials such as polypropylene, polyester, or natural fibers, has been shown in the geotechnical literature to improve the post-peak, ductile behavior of both untreated and chemically stabilized soils by bridging microcracks and providing a random, isotropic reinforcing network within the soil matrix. Polypropylene fiber is of particular interest for sustainable ground improvement because it is chemically inert, resistant to degradation in the alkaline environment created by lime hydration, low in cost, and derived from a widely available polymer. Combining lime stabilization with polypropylene fiber reinforcement therefore offers the prospect of addressing the strength and volumetric-stability benefits of lime treatment together with the ductility and crack-control benefits of fiber reinforcement, within a single, low-cement-content and comparatively sustainable ground-improvement strategy.

Despite a substantial body of research on lime stabilization and on fiber-reinforced soils individually, systematic experimental investigations that combine both treatments and quantify their effect across a full range of lime content, fiber content, and curing period, while also evaluating bearing capacity, swelling, and durability within a single, directly comparable testing program, remain comparatively limited. Existing studies have often examined either the lime dosage effect or the fiber dosage effect in isolation, or have reported results for a narrow set of curing periods, so that the combined, dosage-optimized behavior of lime-fiber treated expansive soil is not documented in a fully comparable format. This gap motivates the present study, which develops and applies a combined experimental framework, referred to as LPFS (Lime–Polypropylene Fiber Stabilization), to systematically evaluate the strength, bearing capacity, swelling, and durability behavior of an expansive clayey soil treated with lime and polypropylene fiber, both individually and in combination.

The principal contributions of this work are: (1) a combined experimental methodology, LPFS, that systematically identifies the optimum lime content on the basis of unconfined compressive strength and then identifies the optimum polypropylene fiber content at that lime dosage; (2) a curing-period-wise comparison of unconfined compressive strength for untreated, lime-only, and lime-fiber treated soil at 7, 28, and 90 days; (3) an evaluation of soaked California Bearing Ratio and free swell index for the three treatment conditions; and (4) a durability assessment of lime-only and lime-fiber treated soil under repeated wet-dry cycling, quantifying the practical significance of fiber reinforcement for moisture-related deterioration.

The remainder of this paper is organized as follows. Section 2 reviews related literature on lime stabilization, fiber reinforcement of soils, and combined lime-fiber stabilization studies. Section 3 presents the proposed LPFS methodology, including soil and material characterization, mix design, specimen preparation, curing, and the testing program.

Section 4 reports the comparative experimental results. Section 5 discusses the findings and their limitations, and Section 6 concludes the paper with directions for future work.

2 Related Work

This section reviews international and Indian research on lime stabilization of expansive soils, fiber reinforcement of soils, and combined lime-fiber stabilization studies, and identifies the gaps that motivate the present study.

2.1 Lime stabilization of expansive soils

Early and continuing research has established that hydrated lime reacts with reactive clay minerals through cation exchange, flocculation-agglomeration, and long-term pozzolanic reaction, collectively reducing plasticity, decreasing swelling potential, and increasing strength and stiffness of expansive soils. Bell reviewed the mechanisms of lime stabilization of clay minerals and soils and reported that most of the plasticity reduction and immediate strength gain occurs rapidly after mixing, while pozzolanic strength gain continues over weeks to months of curing. Al-Rawas, Hago and Al-Sarmi examined the effect of lime and other stabilizers on the swelling potential of an expansive soil and found that lime addition substantially reduced free swell and swelling pressure, with the reduction increasing with lime content up to an optimum beyond which further gains were marginal. Sivapullaiah, Sridharan and Ramesh studied the strength behavior of lime-treated soils and highlighted that, while lime treatment reliably increases peak strength, the treated soil typically exhibits a comparatively brittle stress-strain response with limited post-peak deformation capacity.

2.2 Fiber reinforcement of soils

A parallel body of literature has examined the reinforcement of soils using discrete, randomly distributed fibers. Consoli, Prietto and Ulbrich investigated the influence of fiber and cement addition on the behavior of a sandy soil and found that fiber inclusion increased peak strength modestly but produced a marked improvement in ductility and post-peak strength retention compared to the unreinforced or cement-only soil. Puppala and Musenda examined the effect of fiber reinforcement on strength and volume change in expansive soils and reported reductions in swelling and improvements in strength and stiffness with increasing fiber content, up to a dosage beyond which workability and compaction quality deteriorated due to fiber clustering. These studies collectively establish that discrete fiber reinforcement transforms the brittle failure mode typical of stabilized or compacted clay into a more ductile, gradually degrading response, without requiring the fibers to be oriented or continuous.

2.3 Combined lime-fiber stabilization studies

A smaller number of studies have examined the combined effect of chemical stabilization and fiber reinforcement. Tang, Shi, Gao, Chen and Cai investigated short polypropylene fiber reinforcement of cement-stabilized clayey soil and reported that fiber inclusion increased unconfined compressive strength, increased failure strain, and changed the failure mode from a single brittle crack to multiple, distributed micro-cracks. Cai, Shi, Ng and Tang studied the combined effect of polypropylene fiber and lime addition on the engineering properties of clayey soil and found that the lime-fiber combination produced greater strength and ductility improvement than either treatment applied alone, with an identifiable optimum fiber content beyond which strength gain plateaued or declined. Chen and Wang examined the behavior of fiber-reinforced, lime-stabilized clayey soil under triaxial loading and reported similar trends of increased peak strength, increased failure strain, and a more gradual post-peak stress reduction with fiber addition at a fixed lime content.

2.4 Research gaps

Across these strands of literature, the mechanisms and general trends of lime stabilization and of fiber reinforcement, individually and in combination, are reasonably well established for unconfined compressive strength. However, a single, systematically dosage-optimized experimental program that identifies the optimum lime content, then the optimum fiber content at that lime dosage, and subsequently reports curing-period-wise strength, bearing capacity, swelling, and wet-dry durability behavior within one directly comparable framework is not available in the reviewed literature. The proposed LPFS framework is designed to close this gap.

3 Proposed Methodology

This section presents LPFS (Lime–Polypropylene Fiber Stabilization), the proposed experimental framework for evaluating the combined effect of lime stabilization and polypropylene fiber reinforcement on an expansive clayey soil. The framework comprises six interlinked stages: soil sampling and index property characterization, lime content optimization, polypropylene fiber content optimization, specimen preparation and curing, the strength/bearing/swell/durability testing program, and comparative evaluation, as illustrated in Fig. 1.

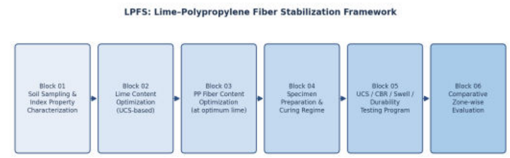

Fig. 1 LPFS framework: six-stage pipeline for soil characterization, lime optimization, fiber optimization, specimen preparation, testing, and comparative evaluation.

3.1 Soil collection and index properties

The soil used in this investigation is an expansive clay collected from a depth of 1.5 m below the natural ground surface, air-dried, pulverized, and passed through a 4.75 mm sieve prior to testing. Index and engineering properties of the untreated soil, including Atterberg limits, specific gravity, free swell index, clay content, and standard Proctor compaction parameters, were determined in accordance with the relevant Indian Standard test methods (Block 01, Fig. 1) and are summarized in Table 1. On the basis of these properties, the soil is classified as a high-plasticity clay (CH) under the IS soil classification system, with a free swell index well above the threshold generally associated with problematic expansive behavior.

Table 1 Index and geotechnical properties of the untreated expansive soil.

Property	Test Method	Value
Liquid limit	IS 2720 (Part 5)	62%
Plastic limit	IS 2720 (Part 5)	24%
Plasticity index	Computed	38%
Free swell index	IS 2720 (Part 40)	92%
Specific gravity	IS 2720 (Part 3)	2.71
Optimum moisture content (untreated)	IS 2720 (Part 7)	19.8%
Maximum dry density (untreated)	IS 2720 (Part 7)	1.62 g/cm^3
Clay content (< 0.002 mm)	Sedimentation analysis	46%
Soil classification	IS 1498	CH

3.2 Materials: hydrated lime and polypropylene fiber

Commercially available hydrated lime [$Ca(OH)_2$], conforming to IS 712 requirements for building lime, was used as the chemical stabilizer. Polypropylene fibers, 12 mm in length, 20–35 microns in diameter, with a specific gravity of approximately 0.91 and a tensile strength in the range of 300–400 MPa, were used as the discrete reinforcing element (Block 02–Block 03, Fig. 1). Both materials were added on a dry-weight-of-soil basis, and the fiber content, Pf, was computed using Eq. (1):

$$Pf = (Wf / Ws) \times 100 \quad (1)$$

where Wf is the dry weight of polypropylene fiber added and Ws is the dry weight of soil. The lime content, expressed on the same dry-weight basis, was varied independently of the fiber content during the lime-optimization stage described in Section 3.3.

3.3 Mix design, specimen preparation, and curing

The mix design was carried out in two sequential stages, consistent with the LPFS framework (Block 02–Block 04, Fig. 1). In the first stage, lime content was varied at 0, 2, 4, 6, and 8% by dry weight of soil, with no fiber addition, to identify the lime content that produced the greatest practical gain in 28-day unconfined compressive strength. In the second stage, polypropylene fiber content was varied at 0, 0.3, 0.6, 0.9, and 1.2% by dry weight of soil at the optimum lime content identified in the first stage, to identify the optimum fiber dosage. For each mix, the soil, lime, and fiber were dry-mixed thoroughly, water was added to the optimum moisture content determined for that mix by standard Proctor compaction (IS 2720, Part 7), and the mixture was statically compacted into cylindrical moulds of 38 mm diameter and 76 mm height for unconfined compressive strength specimens, and into standard CBR moulds for bearing ratio specimens. Specimens were extruded, wrapped to prevent moisture loss, and cured in a humidity-controlled chamber at 27 ± 2°C for 7, 28, or 90 days prior to testing (Block 04, Fig. 1).

3.4 Testing program

Unconfined compressive strength tests were performed in accordance with IS 2720 (Part 10), equivalent to ASTM D2166, at a strain rate of 1.25 mm/min, on specimens cured for 7, 28, and 90 days. Soaked California Bearing Ratio tests were performed in accordance with IS 2720 (Part 16) on specimens cured for 28 days and subsequently soaked in water for 96 hours prior to penetration testing, with the CBR value computed using Eq. (2):

$$CBR = (\text{Test load at 2.5 mm penetration} / \text{Standard load}) \times 100 \quad (2)$$

Free swell index was determined in accordance with IS 2720 (Part 40) on oven-dried, pulverized specimens of each treatment condition. Durability under moisture cycling was assessed using a wet-dry cycling procedure consistent with ASTM D559, in which 28-day-cured specimens were alternately soaked in water for 5 hours and oven-dried at 71°C for 42 hours, brushed with a standard wire-brushing force after each cycle, and weighed to determine cumulative mass loss over 3, 6, and 12 cycles (Block 05, Fig. 1).

3.5 Evaluation setup

All strength, bearing capacity, swelling, and durability results reported in Section 4 were obtained from triplicate specimens for each combination of treatment and curing period, with the mean value reported and the test conditions, mould geometry, compaction effort, and curing regime held identical for the untreated, lime-only, and lime-fiber treated specimens, so that any difference in measured response between the three treatment conditions is attributable to the presence of lime, fiber, or their combination (Block 06, Fig. 1).

4 Experimental Results

This section reports the comparative experimental results obtained for the untreated soil and the lime-only and lime-fiber treated soil, covering the lime-content optimization, the fiber-content optimization, the soaked CBR and free swell index, and the wet-dry durability response.

4.1 Effect of lime content on unconfined compressive strength

Table 2 and Fig. 2 present the 28-day unconfined compressive strength of soil specimens treated with 0, 2, 4, 6, and 8% lime, together with the corresponding optimum moisture content and maximum dry density from standard Proctor compaction. Strength increased steadily with lime content up to 6%, beyond which the additional strength gain to 8% lime was small, indicating that 6% represents the practical optimum lime content for this soil; this dosage was accordingly adopted for the fiber-optimization stage described in Section 4.2.

Table 2 Effect of lime content on compaction parameters and 28-day UCS.

Lime content (%)	OMC (%)	MDD (g/cm³)	28-day UCS (kPa)
0 (untreated)	19.8	1.62	145
2	20.6	1.58	310
4	21.4	1.55	520
6	22.3	1.52	680
8	23.1	1.49	705

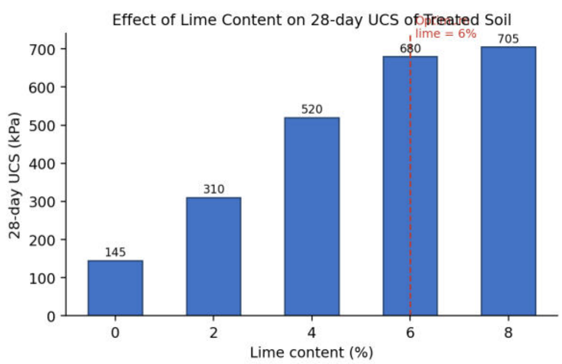

Fig. 2 Effect of lime content on 28-day unconfined compressive strength.

4.2 Effect of polypropylene fiber content on strength and ductility

Table 3 and Fig. 3 compare the unconfined compressive strength of soil treated with 6% lime and polypropylene fiber contents of 0, 0.3, 0.6, 0.9, and 1.2%, tested after 7, 28, and 90 days of curing, together with the failure strain corresponding to peak stress at 28 days. Strength increased with fiber content up to 0.9%, at which dosage the 28-day UCS reached 875 kPa, an increase of approximately 29% over the lime-only mix and close to 500% over the untreated soil; beyond 0.9% fiber, strength declined slightly, consistent with reduced compaction quality caused by fiber clustering (balling) at higher dosages. The failure strain increased consistently with fiber content across the full range tested, rising from 1.2% for the lime-only mix to 4.8% at 1.2% fiber, confirming that fiber reinforcement substantially improves the post-peak ductility of the lime-stabilized soil even where the peak strength itself is marginally reduced at the highest dosage.

Table 3 Effect of polypropylene fiber content (at 6% lime) on UCS across curing periods and on 28-day failure strain.

Fiber content (%)	7-day UCS (kPa)	28-day UCS (kPa)	90-day UCS (kPa)	28-day failure strain (%)
0 (lime only)	410	680	810	1.2

Fiber content (%)	7-day UCS (kPa)	28-day UCS (kPa)	90-day UCS (kPa)	28-day failure strain (%)
0.3	460	760	905	2.4
0.6	505	845	990	3.6
0.9 (optimum)	520	875	1015	4.3
1.2	470	790	930	4.8

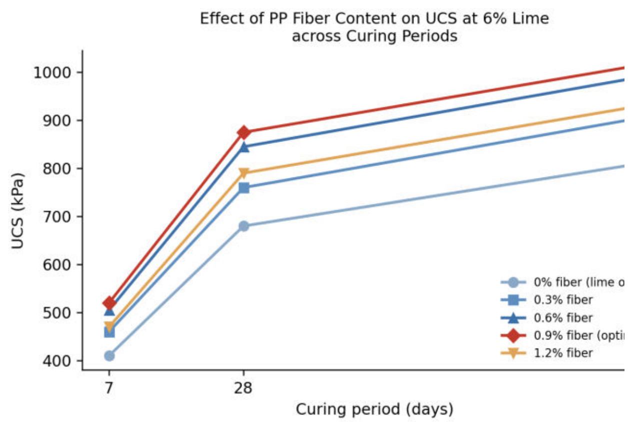

Fig. 3 Effect of polypropylene fiber content on UCS at 6% lime across curing periods.

4.3 Soaked CBR and free swell index

Table 4 and Fig. 4 compare the soaked CBR and free swell index of the untreated soil, the lime-only mix (6% lime), and the combined lime-fiber mix (6% lime, 0.9% fiber). The combined treatment increased the soaked CBR from 2.1% for the untreated soil to 9.4% for the lime-only mix and further to 13.8% for the lime-fiber mix, an overall increase of approximately 557% relative to the untreated condition. The free swell index was reduced from 92% for the untreated soil to 38% for the lime-only mix and to 24% for the lime-fiber mix, corresponding to reductions of 58.7% and 73.9% respectively, confirming that fiber inclusion provides an additional, measurable improvement in volumetric stability beyond that achieved by lime treatment alone.

Table 4 Soaked CBR and free swell index: untreated versus lime-only versus lime-fiber treated soil.

Treatment	Soaked CBR (%)	Free swell index (%)	FSI reduction (%)
Untreated	2.1	92	—
Lime only (6%)	9.4	38	58.7
Lime (6%) + PP fiber (0.9%)	13.8	24	73.9

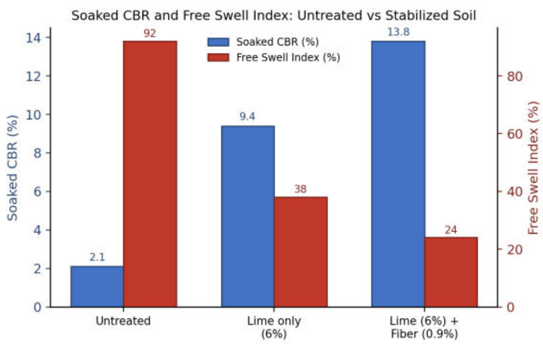

Fig. 4 Soaked CBR and free swell index for untreated, lime-only, and lime-fiber treated soil.

4.4 Durability under wet-dry cycling

Table 5 summarizes the cumulative mass loss of lime-only and lime-fiber treated specimens over 3, 6, and 12 wet-dry cycles; untreated specimens disintegrated within the first wet-dry cycle and could not be evaluated beyond that point. At 12 cycles, the lime-only specimens had lost 24.3% of their initial mass, whereas the lime-fiber specimens had lost only 9.1%, indicating that the fiber network substantially improves resistance to the cracking and progressive disintegration that lime-only specimens experience under repeated moisture cycling.

Table 5 Cumulative mass loss under wet-dry durability cycling (ASTM D559).

Number of cycles	Untreated – mass loss (%)	Lime only (6%) – mass loss (%)	Lime (6%) + Fiber (0.9%) – mass loss (%)
0	0	0	0
3	Disintegrated (> 50% loss)	9.8	4.2
6	—	15.6	6.5
12	—	24.3	9.1

5 Discussion

The results confirm that, while lime stabilization alone produces substantial gains in strength, bearing capacity, and volumetric stability relative to the untreated expansive soil, the addition of polypropylene fiber at an optimum dosage provides further, practically significant improvement across all four performance measures examined: strength, ductility, bearing capacity, and durability. The most notable finding is the change in failure behavior: the lime-only specimens exhibited a comparatively brittle stress-strain response, with a low failure strain of 1.2% at 28 days, whereas the lime-fiber specimens sustained more than three and a half times this strain before reaching peak stress, and continued to carry load in a gradual, distributed manner rather than failing abruptly along a single crack plane. This ductility improvement is of direct practical relevance for subgrade and embankment applications, where post-peak deformation capacity and resistance to progressive cracking under repeated loading and moisture cycling are as important as peak strength itself.

The durability results are of particular practical significance: the lime-only specimens lost nearly a quarter of their mass over twelve wet-dry cycles, a level of deterioration that would be of concern in a subgrade exposed to seasonal moisture variation, whereas the lime-fiber specimens lost less than half this amount, confirming that the fiber network restrains the microcracking that initiates and propagates moisture-induced mass loss in the lime-only material. Combined with the marginal decline in peak UCS observed beyond 0.9% fiber content, these results indicate that fiber dosage should be optimized rather than maximized, since excessive fiber content impairs compaction quality and workability without providing further strength benefit, even though it may continue to contribute additional ductility.

5.1 Limitations of the study

Several limitations should be acknowledged. First, the investigation considers a single expansive soil source and a single fiber type, length, and diameter; the optimum lime and fiber dosages identified here may differ for soils of different mineralogy or plasticity, or for fibers of different geometry and surface characteristics. Second, curing was carried out under controlled laboratory humidity and temperature conditions, which may not fully represent field curing under variable moisture and temperature exposure. Third, the durability assessment was limited to twelve wet-dry cycles and did not include freeze-thaw cycling, which may be relevant in cooler climates. Finally, the study evaluated unconfined compressive strength, CBR, swelling, and mass-loss durability, but did not include direct shear, triaxial, or full-scale field trial data, which would be valuable for extending the findings to design practice.

6 Conclusion and Future Work

This study presented LPFS, a combined experimental framework for evaluating the strength, bearing capacity, swelling, and durability behavior of an expansive clayey soil treated with hydrated lime and polypropylene fiber, individually and in combination. Six percent lime content was identified as the practical optimum on the basis of 28-day unconfined compressive strength, and 0.9% polypropylene fiber content was identified as the optimum fiber dosage at this lime content. The combined lime-fiber treatment increased 28-day UCS by approximately 500% and soaked CBR by approximately 557% relative to the untreated soil, reduced the free swell index by nearly 74%, more than tripled the failure strain at peak stress relative to the lime-only mix, and more than halved the mass loss under wet-dry durability cycling relative to the lime-only mix. These results demonstrate that combined lime and polypropylene fiber stabilization offers a sustainable, comparatively low-cement-content ground-improvement strategy that addresses the strength, stiffness, volumetric-stability, ductility, and durability requirements of expansive subgrade soils more comprehensively than lime treatment alone.

Future work will extend the LPFS framework to additional expansive soil sources of varying plasticity and mineralogy, to alternative and blended fiber types including natural and hybrid synthetic fibers, and to field-scale trial embankments and pavement subgrades instrumented for long-term moisture and deformation monitoring. Additional laboratory work incorporating triaxial shear testing, freeze-thaw durability cycling, and life-cycle carbon-footprint comparison against higher-cement-content stabilization alternatives would further support the adoption of lime-fiber stabilization as a sustainable ground-improvement practice.

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