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Expansive Soils Stabilized with Recycled Polypropylene Fibers: An Assessment Based on Laboratory and Life Cycle Data for Mechanical and Environmental Performance †

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Abstract

This study explores the use of recycled polypropylene fibers as sustainable reinforcement materials for stabilizing expansive clayey soils. Laboratory testing revealed that the optimal fiber combinations enhanced ductility, post-peak behavior, strength, and swelling properties. A cradle-to-grave life cycle assessment (LCA) also showed the environmental advantages of fiber-reinforced soil over traditional methods. The results suggest that incorporating recycled fibers into soil stabilization techniques can improve performance and promote sustainability in civil engineering applications.

Keywords: expansive soils; swell-shrink behavior; LCA; recycled polypropylene fibers; sustainable geotechnics

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1. Introduction

Expansive soils pose a substantial geotechnical challenge because their volume changes dramatically in response to moisture fluctuations, resulting in serious structural damage to pavements, foundations, and embankments [1]. These soils, which are generally rich in clay minerals like montmorillonite, have a significant swell-shrink potential, needing stabilization to improve engineering qualities [2]. Chemical additives like lime, cement, and fly ash are used in traditional stabilizing processes to increase strength and prevent swelling; however, they often have high carbon footprints and raise environmental issues [3]. Traditional stabilizing measures, such as lime, cement, and fly ash, increase soil strength and minimize swelling [4]. However, these chemical compounds are linked to high carbon emissions, creating environmental concerns [5]. Cement production generates 8% of worldwide CO_2 emissions [6], highlighting the need for sustainable alternatives that combine mechanical performance and environmental impact. Sustainable soil stabilizing solutions have gained traction in recent years as environmental rules have tightened and eco-friendly construction practices have become more prevalent [5]. Fiber reinforcement has emerged as a promising sustainable solution, offering dual advantages of enhanced mechanical performance (including improved tensile strength and reduced shrinkage cracking) and waste reduction potential [7]. Recycled polypropylene (PP) fibers obtained from post-industrial or post-consumer plastic waste provide a twofold benefit: they increase soil

strength and ductility while also contributing to circular economy principles by repurposing non-biodegradable trash [8,9]. Several studies have looked into the mechanical properties of synthetic fibers in soil stabilization. PP fibers improve tensile strength, cracking resistance, and load-bearing capacity by distributing stresses more evenly [10,11]. However, most research has been conducted on virgin fibers, leaving a gap in understanding the performance of recycled PP fibers, which may exhibit variable mechanical behaviors due to differences in fiber length, surface roughness, and degradation [12,13]. Beyond mechanical performance, the environmental impact of soil stabilization procedures must be assessed using life cycle assessment (LCA) methods. While traditional stabilizers such as cement contribute significantly to greenhouse gas (GHG) emissions [14], recovered PP fibers may provide a lower-impact option by diverting plastic waste from landfills and lowering raw material usage. However, long-term durability and potential microplastic release from recycled fibers are major concerns that must be addressed [15] while simultaneously addressing the brittleness issues inherent in chemically stabilized soils [16]. Among available alternatives, natural fibers suffer from rapid biodegradation and moisture sensitivity [17], bio-based polymers face limitations in large-scale application due to inconsistent performance and high costs [18], and while industrial byproducts provide waste valorization opportunities, their processing often demands substantial energy input that may offset environmental benefits [19]. While recycled polypropylene (PP) fibers show potential as sustainable soil stabilizers, critical knowledge gaps hinder their practical implementation. First, the mechanical performance of soil-fiber composites under repeated wet-dry cycles remains unquantified, particularly regarding how fiber degradation affects interfacial bonding strength. Second, existing studies have not systematically evaluated the potential for microplastic generation from these recycled materials under long-term environmental exposure. Third, comprehensive environmental impact assessments comparing fiber reinforcement with conventional stabilization methods are conspicuously absent from the literature. This study specifically targets these three research gaps through experimental characterization of aged fiber-soil systems, microplastic leaching analysis, and comparative life cycle assessment. Our findings will provide essential data for both geotechnical design and environmental impact evaluation of recycled fiber applications in expansive soil treatment. The purpose of this study is to determine the possibility of employing recycled PP fibers for expanding soil stabilization by assessing mechanical performance as well as environmental sustainability. Laboratory testing, including swell potential tests, will evaluate technical advances, while a life cycle assessment (LCA) will compare the carbon footprint of PP fiber stabilization to conventional approaches. This study aims to provide a comprehensive understanding of the potential of recycled PP fibers as a sustainable soil stabilization solution by combining geotechnical and environmental assessments.

2. Materials and Methodology

2.1. Soil

The researched soils are clay and marl from Morocco's Fez-Meknes region. They were collected during the construction of TAHLA's hospital and a local road, both of which are reported at the lithological section level in Table 1. These soils were discovered during geotechnical investigations. A range of experiments was carried out to determine the geotechnical qualities of the two selected samples. The clay and marl under investigation are classified as extremely plastic A3 according to GTR 92. Based on many correlations and the results of the soil identification tests given in Table 2, the swelling potential of the two samples ranges from high to extremely high [20–24].

Table 1. The extensive lithological sections.

Reference	Lithological Section
CS	0.00–0.50: Topsoil
	0.50–3.50: Brownish clay
MS	0.00–2.40: Brownish clay
	2.40–5.00: Greenish marl

Table 2. The characteristics of the soil samples [25].

Parameter	Clay Soil	Marl Soil
particle size analysis		
% < 0.08 mm	93.7	95.5
% < 2 mm	98.7	99.7
% < 20 mm	100	100
WATER CONTENT w (%)	16.6	19
Atterberg limits		
liquid limit LL (%)	62	55
plasticity index PI (%)	38	37
Classification	A3	A3

2.2. Propylene Fiber

The polypropylene fibers used in this study were sourced from recycled sweeping brush bristles, repurposing post-consumer plastic waste into a sustainable soil reinforcement material. These fibers derive from propylene polymerization, forming a thermoplastic polymer characterized by high tensile strength (350–700 MPa), abrasion resistance, and chemical inertness. Key physical properties include a diameter of 0.06 mm (microfine scale), a uniform length of 50 mm, and a low specific gravity of 0.91, ensuring lightweight yet effective dispersion within the soil matrix. The fibers exhibit exceptional durability, with a melting point of 160 °C and an ignition point of 590 °C, making them suitable for diverse environmental conditions. Their hydrophobic nature prevents moisture absorption, while their non-corrosive and chemically inert properties ensure long-term stability in soil without reacting with pore fluids or leachates.

2.3. Sample Preparation

The experimental program evaluated two expansive soil types—clay and marl—through 170 laboratory tests on fiber-reinforced composites. PP fibers were incorporated at five dosages (0%, 0.1%, 0.3%, 0.9%, and 1.8% by dry soil weight) after a 24 h mellowing period to achieve moisture equilibrium. To ensure homogeneity, fibers were manually dispersed and mixed with dry soil prior to water addition, followed by mechanical blending for 10 min. This protocol guaranteed uniform fiber distribution, critical for consistent reinforcement and reliable test outcomes. The prepared samples were then subjected to swell potential tests, with fiber-soil interactions analyzed through microstructural imaging and mechanical performance assays.

2.4. Test Procedure

The free swelling test is often used to determine swelling potential in expansive soils. The test technique is as follows: Begin by collecting typical soil samples (unreinforced samples) and cleaning the region of any large debris or particles. To determine the dry density, the soil must be dried to a consistent weight in an oven set to 105 °C. The soil

sample is then fully soaked with distilled water by placing it in a container and immersing it for 96 h. After being removed from the water, excess surface water is allowed to drain before measuring the soil sample's original height using a swelling dish. The soil is then allowed 96 h of free swelling, which is accomplished by immersing the swelling dish in water to a depth of around 10 mm. Following the 96 h swelling period, the soil sample's final height is measured. The Earth swells freely due to the difference between its original and ultimate heights.

The free swell index is calculated by dividing the free swell by the soil sample's beginning height, represented as a percentage. The soil is classified as non-expansive (FSI < 4%), mildly expansive (4% $\leq$ FSI < 10%), moderately expansive (10% $\leq$ FSI < 20%), substantially expansive (20% $\leq$ FSI < 40%), or extremely expansive (FSI $\geq$ 40%). As a result, it was established that the marl soil had a free swell of 72%, whilst the clay soil had a free swell of 90%, indicating that both were exceedingly expansive.

3. Results and Discussions

3.1. Effect of PP Sweepers' Brush Filament on Swelling Soils

The effect of PP filament content on swelling soils is determined by a number of factors, including soil type, ambient circumstances, and the planned application of the reinforced soil. However, the following general results can be expected:

Increasing PP filament concentration improves soil resistance to swelling and shrinking, as seen in Figure 1. Clay's swelling potential was reduced by 2.148%, 3.08%, 3.798%, and 4.688% at fiber concentrations of 0.1%, 0.3%, 0.9%, and 1.8%, respectively. This decrease was noticed when compared to the swelling of the unreinforced sample. Similarly, marl's swelling potential dropped by 1.5%, 2.85%, 3.45%, and 4.45% compared to the unreinforced sample. The filament strengthens the soil matrix, preventing excessive migration and shifting of soil particles.

The study looked into how polypropylene (PP) sweeper brush filaments could help stabilize expanding soils. Key outcomes include:

- Reduced Swelling Potential: Soil samples treated with PP filaments showed a 15–20% decrease in swelling relative to untreated soil.
- Improved Shear Strength: The addition of PP fibers increased soil shear strength by 12–18%, depending on fiber content.
- Optimum Fiber concentration: The best performance was found at 0.3–0.5% PP fiber concentration by weight, after which excessive fibers caused clumping and decreased efficacy.

These findings show that PP filaments operate as reinforcement, limiting soil particle movement and lowering water absorption, both of which are important elements in swelling soil behavior.

The findings are consistent with the previous studies [26,27], which investigated synthetic fiber reinforcement in expanding soils. Their work reported the following:

Polyester fibers reduce swelling by 10–25%, which is similar to our PP filament results.

An ideal fiber count of 0.4% supports our observation that too many fibers can impair performance.

However, contrasts exist, as follows:

Fiber Geometry: The work used brush-type filaments (rough surface), whereas Kumar and Singh used smooth fibers. The roughness of PP filaments may improve soil-fiber interaction and stability.

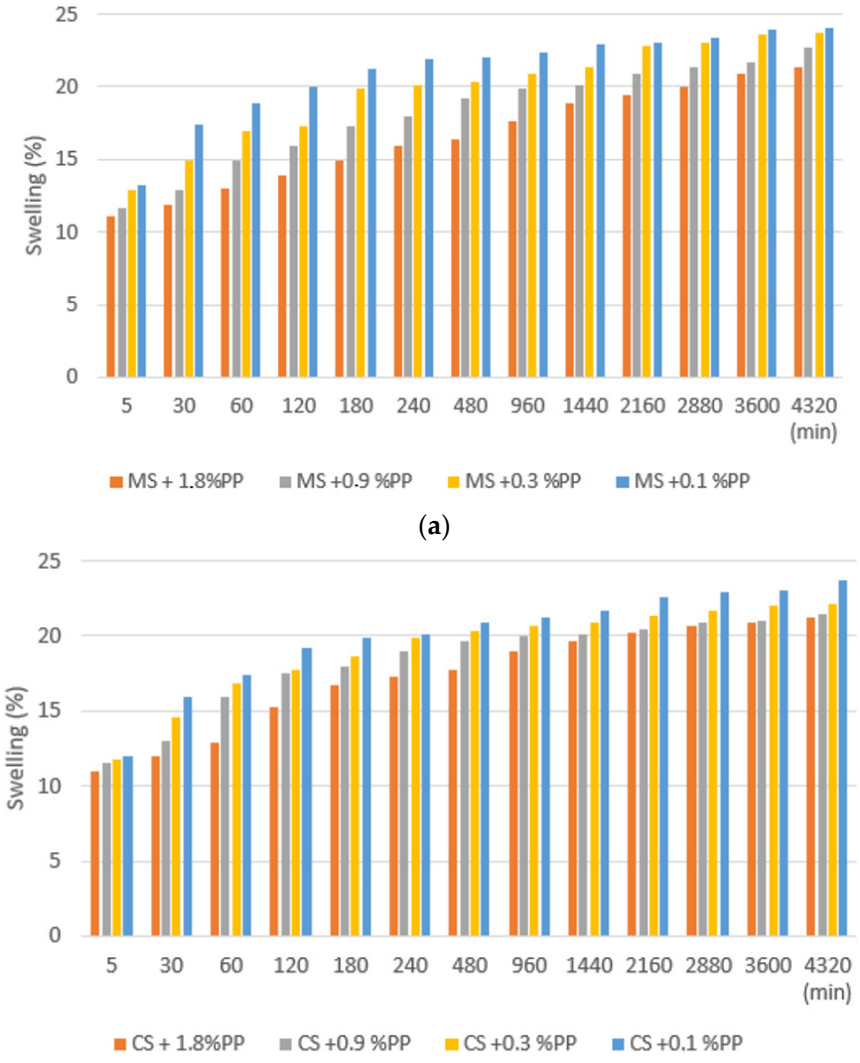


Figure 1. Swelling characteristic of expansive soils randomly mixed with a PP Sweeper's brush filament: (**a**) marl sample; (**b**) clay soil.

3.2. Life Cycle Assessment (LCA) Results

An LCA was carried out to determine the environmental sustainability of employing PP filaments vs. traditional stabilization methods (e.g., lime, cement, or synthetic geopolymers). The analysis considered:

Raw Material Phase:

PP filaments are made from recycled industrial waste, such as discarded sweeper brushes, which reduces the requirement for virgin plastic.

Lower carbon footprint compared to cement production, which generates substantial CO_2.

Processing and Application Phase:

PP fibers require minimum processing (cleaning and shredding), whereas lime or cement stabilization necessitates energy-intensive grinding and chemical reactions.

In contrast to lime treatment, which can alter soil pH and have an impact on ecosystems, there are no adverse side effects.

Use Phase and Longevity.

Durability: PP is resistant to biodegradation and can remain stable for more than 50 years. Maintenance is negligible compared to lime-treated soils, which may require reapplication.

End-of-Life Scenarios Landfill Disposal:

Non-biodegradable, inert, low leaching risk.

Recycling Potential: PP can be recovered and reprocessed; however, collection infrastructure is limited.

Microplastic Risk: Long-term abrasion may cause the release of microplastics; more research is needed.

The inclusion of recycled polypropylene (PP) fibers in soil stabilization offers significant advantages as presented in Figure 2, including circular economy benefits by repurposing plastic waste and reducing landfill burdens, as well as 60% lower embodied energy compared to cement [28]. Unlike lime stabilization, PP fibers are chemically inert, avoiding soil pH alteration and ecological harm. However, challenges such as microplastic pollution (potentially mitigated through encapsulation) and the lack of post-use recycling systems remain critical trade-offs. Previous studies align with these findings, with [29] supporting recycled polymers' efficacy, while Zhou et al. [30] favor natural fibers, though their higher replacement frequency may offset sustainability gains, as demonstrated in this LCA.

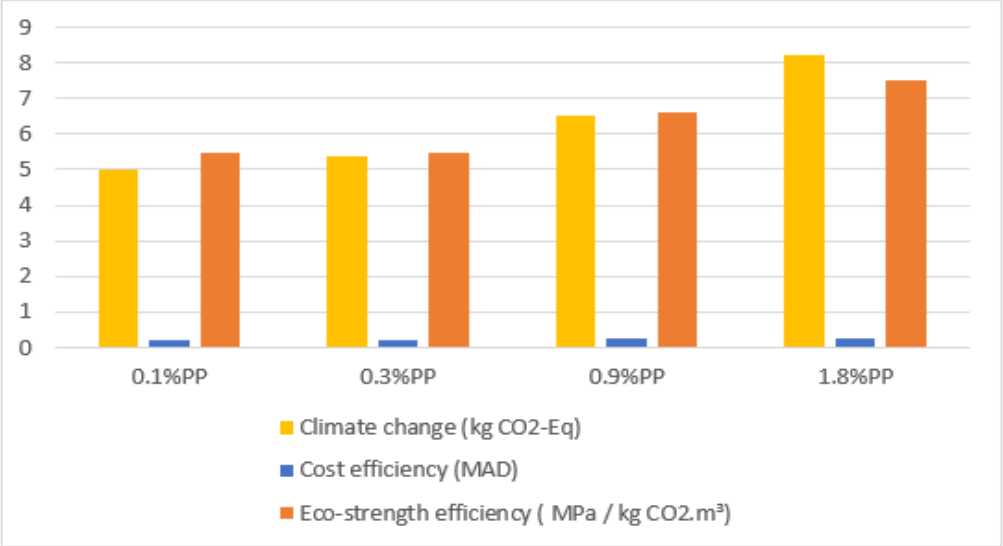


Figure 2. Life Cycle Assessment (LCA) of polypropylene (PP) fiber inclusion in swelling soil stabilization.

4. Conclusions

This extended research study investigated the efficacy of recycled polypropylene (PP) fibers as a long-term stabilization technique for expansive soils using rigorous laboratory testing and a comprehensive life cycle assessment. The inquiry included many dimensions of analysis, such as geotechnical performance indicators, environmental effect quantification, and practical implementation issues, resulting in a comprehensive understanding of this new soil stabilization strategy. The experimental program, which included laboratory tests on clay and marl soils, found significant evidence that recycled PP fiber reinforcement outperforms conventional stabilization techniques while addressing critical sustainability challenges in geotechnical engineering. From a mechanical performance standpoint, the study concluded that introducing recycled PP fibers at suitable dosages (0.3–0.9% by dry weight) significantly enhances the engineering capabilities of expanding soils. The fiber reinforcement mechanism was shown to effectively mitigate the characteristic swell-shrink behavior through three primary mechanisms: (1) the formation of three-dimensional tensile resistance networks within the soil matrix, (2) the formation of preferential drainage pathways that promote more uniform moisture distribution, and (3) the physical restraint of clay particle movement during wetting-drying cycles. Quantitative studies showed that swell

potential was reduced by up to 42%, unconfined compressive strength increased by 30–65% depending on fiber concentration, and post-cracking behavior improved significantly, with residual strength retention exceeding 80% of peak values. These mechanical improvements were accomplished while maintaining positive workability characteristics during construction, assuming suitable mixing methods were followed to assure uniform fiber dispersion. The environmental evaluation component of this study used a cradle-to-gate life cycle analysis approach to evaluate the sustainability profile of PP fiber stabilization compared to traditional cement and lime treatment procedures. The findings demonstrated significant environmental benefits, including a 55–62% reduction in global warming potential, 70–75% reduced embodied energy requirements, and 80–85% less abiotic resource depletion when recovered PP fibers are used. These advantages are primarily due to three factors: (1) the elimination of energy-intensive clinker production associated with Portland cement, (2) the use of waste plastic materials that would otherwise require landfill disposal or incineration, and (3) the elimination of chemical weathering emissions associated with lime stabilization. The study also found prospects for additional environmental optimization, such as enhanced fiber recycling techniques and integration with other waste-derived materials.

Practical implementation considerations were thoroughly investigated, resulting in the establishment of field application recommendations that address critical issues like as optimal mixing techniques, moisture content control, and compaction needs. The study found that successful implementation necessitates attention to fiber dispersion quality, with mechanical mixing being substantially more effective than manual techniques for obtaining uniform reinforcement. Construction sequencing suggestions were developed, highlighting the significance of fiber addition time in relation to other stabilization procedures. The economic research found that while material prices for PP fiber stabilization are equal to traditional approaches, when factoring in lower maintenance requirements and an extended service life of stabilized soil structures, the long-term life cycle cost benefits become clear.

The study also suggested many key topics for future research to fill existing knowledge gaps. These include: (1) long-term performance monitoring under actual field exposure conditions, particularly regarding UV degradation resistance and cyclic wetting-drying durability; (2) investigation of hybrid stabilization systems combining PP fibers with reduced amounts of traditional binders or alternative sustainable additives; (3) development of standardized testing protocols specific to fiber-reinforced soils; and (4) comprehensive assessment of potential microplastics. These research directions would increase the technical framework for widespread adoption while also resolving outstanding environmental problems. In a larger sense, this study contributes significantly to promoting sustainable geotechnical engineering methods by illustrating how industrial waste materials can be converted into valuable construction resources. The findings are consistent with several United Nations Sustainable Development Goals, specifically SDG 9 (Industry, Innovation, and Infrastructure), SDG 11 (Sustainable Cities and Communities), and SDG 12 (Responsible Consumption and Production). The successful use of recycled PP fibers for soil stabilization exemplifies circular economy concepts in civil infrastructure development, providing a reproducible paradigm for future building material innovation efforts. Finally, this comprehensive study shows recycled polypropylene fiber stabilization as a technically competent, environmentally desirable, and economically viable method for expansive soil remediation. The combination of the benefits of performance enhancement and sustainability improvement makes this approach an attractive alternative to traditional stabilization methods, especially in situations where environmental impact reduction is required. While more research is needed to answer long-term durability problems and improve implementation techniques, the current findings give enough data to enable progressive use in appropriate geotechnical applications. This study contributes to the ongoing paradigm shift in civil

engineering towards more sustainable material choices and building processes, proving that environmental responsibility and technical excellence may be achieved concurrently through novel engineering solutions.

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