COMPARATIVE ANALYSIS OF EXPANSIVE SOIL STABILIZATION: NATURAL VS. INDUSTRIALIZED MATERIALS AND RECYCLED WASTE IN THE MCT METHOD

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Abstract

Expansive soils pose geotechnical challenges due to volumetric changes in the presence of water, being common in the region of Pelotas/RS. This study evaluates the efficiency of different stabilizing agents — lime, Construction and Demolition Waste (CDW), and natural Butia fibers — in mitigating the expansiveness of a clayey soil. The methodology is based on the MCT (Miniature Compacted Tropical) method, analyzing water penetration and diametrical shrinkage of specimens molded with different additive contents. Previous results indicate that lime shows superior performance in delaying the wet front, while CDW acts as a filler material with limitations as a primary stabilizer. The inclusion of Butia fibers (BF) proposes a sustainable mechanical reinforcement mechanism, aiming to reduce cracking and improve dimensional stability. This work contributes to the development of low-environmental impact solutions by comparing traditional methods and innovations based on regional biodiversity.

Keywords: Butia fiber, Construction waste, Expansive soils, Lime, Soil stabilization.

INTRODUCTION

Expansive soils represent one of the greatest challenges for global geotechnical engineering, being characterized by high volumetric instability in response to variations in moisture content. According to Calegaro et al. (2024), this expansive behavior stems from the mineralogical constitution of the soil, wherein the presence of clay minerals from the smectite group — which possess a 2:1 crystalline structure — allows the intercalation of water molecules between their layers, leading to pronounced swelling and shrinkage processes during wetting and drying cycles. In the region of Pelotas/RS, the occurrence of these soils is significant, demanding stabilization methods that ensure the structural integrity of pavements and foundations.

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Historically, chemical stabilization using lime has been the predominant technical solution, particularly in tropical and subtropical soils. According to Nogami and Villibor (2024), the application of lime promotes immediate microstructural modifications, such as flocculation and cation exchange, followed by long-term pozzolanic reactions that increase cohesion and reduce the plasticity of the soil-additive system. However, although the effectiveness of lime in controlling expansive soils is widely documented in the literature (Al-Rawas et al., 2023), the environmental impact associated with its industrial production and the growing demand for circular economy practices have driven the investigation of alternative materials.

In this context, the utilization of Construction and Demolition Waste (CDW) emerges as an alternative for managing urban environmental liabilities, with studies indicating its viability in geotechnical applications (Farias et al., 2023). Nevertheless, its effectiveness as a primary stabilizing agent in fine-grained soils still presents limitations due to its predominantly inert nature and strong grain-size dependency (Kianimehr et al., 2019).

Concurrently, soil reinforcement using natural fibers presents an innovative and sustainable frontier. Studies such as those by Hejazi et al. (2012) and Gowthaman et al. (2018) suggest that the inclusion of fibers significantly improves shear strength and controls desiccation cracking propagation, acting as a mechanical anchoring network that restricts the movement of clay particles. Within the local scenario, the use of Butia fiber arises as a proposal to enhance regional biodiversity, seeking to align technical performance with the availability of natural biopolymers, as preliminarily explored by Tins et al. (2025).

This chapter proposes a novel comparative analysis, utilizing the MCT (Miniature Compacted Tropical) method to evaluate the efficiency of three distinct approaches: the established industrial method (lime), the reuse of CDW, and the application of natural biopolymers (Butia fiber). The objective is to quantify water penetration and diametrical shrinkage parameters, discussing the potential for replacing or complementing conventional materials with low-environmental-impact alternatives.

LITERATURE REVIEW

NATURE AND BEHAVIOR OF EXPANSIVE SOILS

The problematic nature of expansive soils is intrinsically linked to their mineralogical composition, specifically the presence of clay minerals from the smectite group. These minerals are characterized by a 2:1 crystalline structure, composed of two silica tetrahedral sheets sandwiching an aluminum octahedral sheet. According to Grim (1968) and Mitchell & Soga (2005), this configuration results in weak interlaminar bonds held by Van der Waals forces and a deficient charge balance. This allows water molecules to easily enter the interlayer spaces, causing significant volumetric expansion (swelling).

Geotechnically, this behavior translates into high susceptibility to volume change in response to fluctuations in moisture content. When saturated, these soils exhibit a drastic reduction in shear strength and a significant increase in erosivity (Das, 2014). Conversely, the desiccation process leads to severe material shrinkage, resulting in macro-cracks that propagate structural failures and compromise the stability of civil works, such as shallow foundations and pavements (Al-Rawas & Goosen, 2006).

In the region of Pelotas/RS, particularly in areas such as the Quartier neighborhood, these soils are classified as solodic and present a predominantly non-lateritic clayey texture. The analysis of these materials via the MCT method and specimen testing confirms a highly expansive behavior, making stabilization a mandatory step to enable their engineering application. According to Calegaro et al. (2024), the use of reinforcement agents alongside chemical or physical stabilizers has been explored in the region as a viable solution to mitigate structural damage caused by these local geological formations.

CHEMICAL (LIME) AND PHYSICAL (CDW) STABILIZATION

The utilization of additives for expansive soil improvement primarily aims to alter the clay mineral's affinity for water or modify the porous matrix structure to enhance its mechanical strength.

Stabilization through chemical methods is historically well-established, with lime being recognized as one of the most effective chemical agents for smectite-rich soils. As detailed by Sherwood (1993), the process occurs in two consecutive stages: initially, rapid cation exchange and flocculation reduce the thickness of the diffuse double layer, immediately decreasing soil plasticity and improving workability. Subsequently, long-term pozzolanic reactions take place, where the high pH induces the dissolution of amorphous silica and alumina from the soil, which react with free calcium to form hydrated calcium silicates and aluminates (C-S-H and C-A-H). These cementitious compounds bind the clay particles together, ensuring long-term dimensional stability (Nogami & Villibor, 2024).

Unlike lime, Construction and Demolition Waste (CDW) acts predominantly through physical mechanisms of grain-size stabilization. When incorporated into the soil, CDW functions as a rigid granular skeleton that aids in void filling and proportionally reduces the active (expansive) fine content within the total mixture (Arulrajah et al., 2014). However, its isolated technical effectiveness is highly dependent on the particle size distribution and mineralogical composition of the waste, presenting severe limitations as a primary stabilizer when unaccompanied by complementary chemical reactions or a compaction effort that effectively seals preferential water percolation paths (Mohammadinia et al., 2016). The comparative analysis of these methods allows an understanding of the balance between the superior technical performance of lime and the ecological potential of CDW within a circular economy framework.

MECHANICAL REINFORCEMENTED WITH NATURAL FIBERS

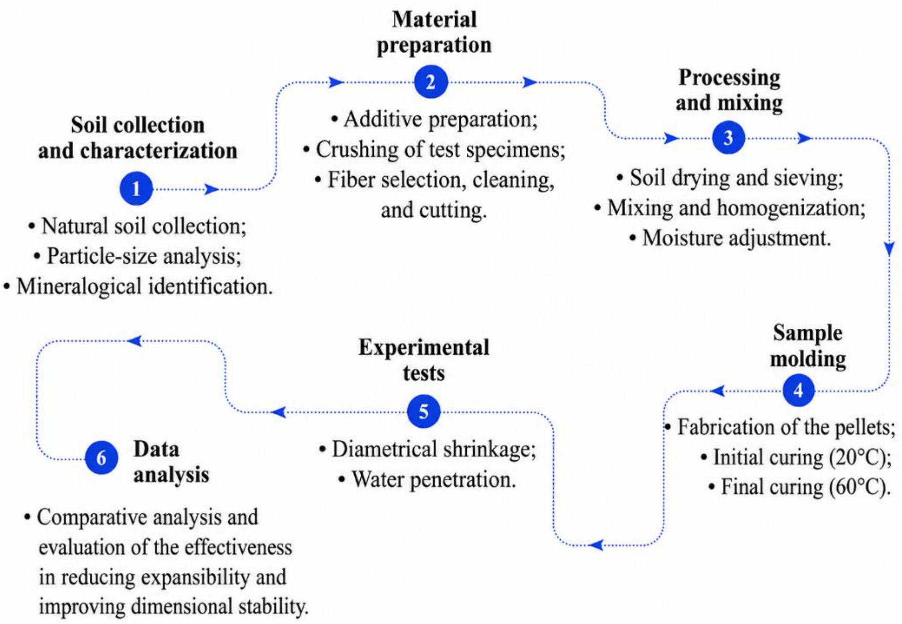
The inclusion of natural fibers in expansive soils introduces an essentially physical-mechanical stabilization mechanism, frequently described in the literature as a tension-transfer bridge (Tang et al., 2007). When randomly distributed throughout the soil mass, the fibers act as three-dimensional reinforcement elements that intercept failure planes and volumetric expansion fronts. The efficiency of this system relies heavily on the quality of the soil-fiber interface, where surface friction, filament roughness, and mechanical adhesion between components govern the transfer of stresses from the clay matrix to the reinforcement element (Gowthaman et al., 2018).

Consequently, when the soil initiates the swelling process due to water absorption, the fibers are subjected to tensile stress, generating a local confining pressure that restricts the movement of smectite particles and reduces the overall magnitude of expansion. Complementarily, during moisture loss, these fibers act as clamps or bridges that stitch together the edges of forming micro-cracks. This mechanism prevents tensile stresses generated by desiccation from evolving into macroscopic fissures, thereby preserving the continuity and structural integrity of the soil mass. As highlighted by Hejazi et al. (2012), the primary advantage of this method lies in the fibers' capacity to convert the brittle and unstable behavior of clayey soil into a markedly ductile behavior, considerably increasing shear strength and dimensional stability without relying exclusively on chemical reactions.

METHODOLOGY

Figure 1

Experimental methodology flowchart



Source: Author (2026)

The experimental design of this study was structured to allow a direct comparison between different stabilization methods, based on the MCT method for the evaluation of tropical and subtropical soils. The research followed a logical sequence that included everything from the granulometric and mineralogical characterization of the natural soil to the performance testing of the mixtures with industrial, recycled, and natural additives, as previously presented in Figure 1.

MATERIALS AND CHARACTERIZATION

The soil used was collected in the Quartier neighborhood, in Pelotas/RS, and was identified as a solodic soil with a clayey texture and highly expansive behavior due to the presence of smectites. To modify its geotechnical behavior, three agents with distinct natures were selected:

a) Hydrated Lime: Representing the consolidated industrial method, applied at 3% and 6% contents.

b) Construction and Demolition Waste (CDW): Material originating from concrete and mortar crushing, also tested at 3% and 6% proportions.

c) Butia Fibers (BF): Representing the natural and sustainable alternative. The fibers, passing through the 1.19 mm sieve, were processed and incorporated into the soil matrix at contents of 1.0%, 2.5%, and 5.0% relative to the dry soil mass.

For mixtures containing fibers, the experimental schedule provided for curing periods of 7 and 28 days, allowing for the observation of the influence of time on the interaction between the natural filaments and the clayey matrix, especially regarding dimensional stability and resistance to water penetration.

EXPERIMENTAL PROCEDURE AND SAMPLE PREPARATION

The experimental rigor followed a chronological sequence divided into six fundamental stages, based on adaptations of the MCT (Miniature Compacted Tropical) method for expedited tests on pellets. Initially, the natural soil was collected from the surface layer (0.00 to 0.50 m) in the Quartier neighborhood, in Pelotas/RS. The soil was subjected to initial geotechnical characterization, including grain-size analysis by sedimentation and sieving (according to current technical standards) and qualitative mineralogical identification, confirming the predominance of active smectite clay minerals.

In the material preparation phase, residual laboratory specimens (concrete and mortar) were crushed in a jaw crusher and quartered to obtain Construction and Demolition Waste (CDW) in fine fractions. In parallel, Butia fibers (BF) were washed in distilled water to remove superficial organic impurities, air-dried, and cut uniformly with the aid of blades, being subsequently selected by passing entirely through a 1.19mm sieve (No. 16 mesh).

Subsequent processing consisted of pre-drying the natural soil in a thermostatically controlled oven at 60°C until constant mass, followed by crushing and complete sieving through the No. 200 (0.075mm) mesh. Subsequently, the additives were weighed and manually dosed in relation to the dry mass of the soil, homogenizing the mixtures dry. The adjustment of the optimum moisture content was performed gradually with distilled water until the matrix reached a standardized plastic consistency, the homogeneity of which was controlled via an adapted penetration test, using the free fall of a standard 1mm needle under constant weight.

The molding of the samples was executed through static compaction of the wet mass inside rigid PVC rings with nominal dimensions of 21mm in diameter and 5mm in thickness, ensuring the repeatability of the dry apparent specific mass of the specimens. The structured curing process occurred on two fronts: all samples were subjected to an initial curing in a wet chamber for 24 hours at a controlled temperature of 20°C (± 2°C), followed by induced desiccation in an oven at 60°C for a period of 4 hours to promote initial water stabilization. For the series additivated with Butia fibers, the curing periods in a protected environment were extended to 7 and 28 days before the terminal desiccation process, allowing for the temporal monitoring of the adhesion at the soil-fiber interface.

The definitive experimental tests evaluated two macroscopic degradation parameters: diametrical shrinkage and resistance to water penetration. Diametrical shrinkage was quantified immediately after leaving the oven, using a manual mechanical caliper (0.05mm precision) adjusted to perform readings on three orthogonal axes previously marked on the pellets, obtaining the arithmetic mean of the deformations. Finally, the water penetration test consisted of partially immersing the dry pellets in cuvettes filled with distilled water. The resistance to penetration and the evolution of the material's softening were quantified using a manual penetrometer equipped with a dial gauge. The equipment was positioned perpendicularly on the upper surface of each pellet, applying the stroke of the standard needle to record the penetration depth (in millimeters) at strict time intervals of 5, 15, and 30 minutes, followed by control readings at 2 and 24 hours. The collected data were tabulated for the consolidation of a comparative statistical analysis focused on the efficiency of each stabilizing agent.

DISCUSSION AND RESULTS

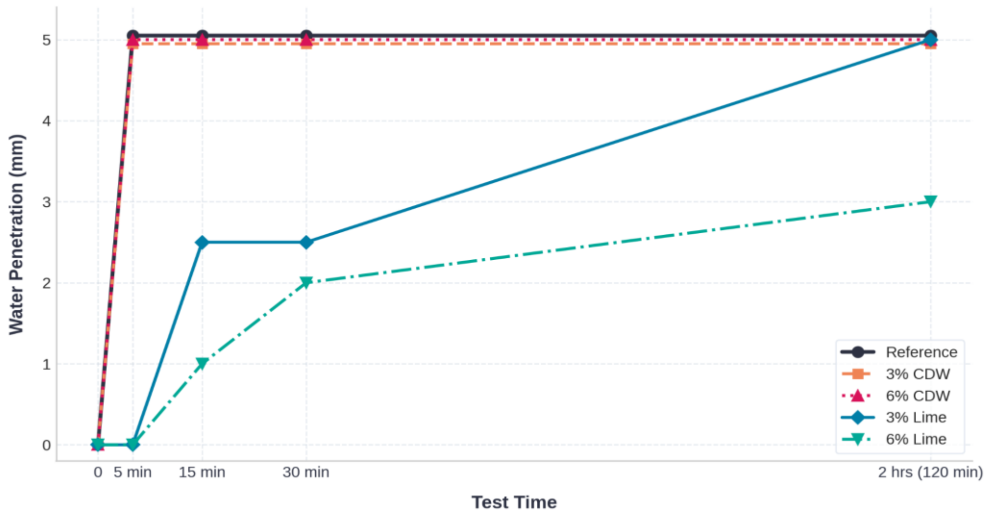
EFFICIENCY IN WATER PENETRATION RESISTANCE

Water penetration analysis allows for the evaluation of the stabilizing agents' capacity to modify the soil pore network and reduce its affinity for water, a critical factor in controlling expansiveness. The obtained results reveal significant contrasts among the chemical, physical, and mechanical approaches.

Regarding conventional and recycling methods, the specimens treated with Construction and Demolition Waste (CDW) showed a low capacity to delay the advancement of the wetting front, reaching the maximum penetration of 5mm within the first 5 minutes of the test. This behavior highlights that CDW, in its inert form, did not promote effective pore sealing. Conversely, as observed in Figure 2, the consolidated efficiency of lime is evident in delaying full saturation up to the 2 hours interval, especially at the 6% content, where softening and penetration depth progressed gradually due to pozzolanic reactions and structural modification of the clay matrix.

Figure 2

Water penetration as a function of time for reference soil, lime, and CDW.

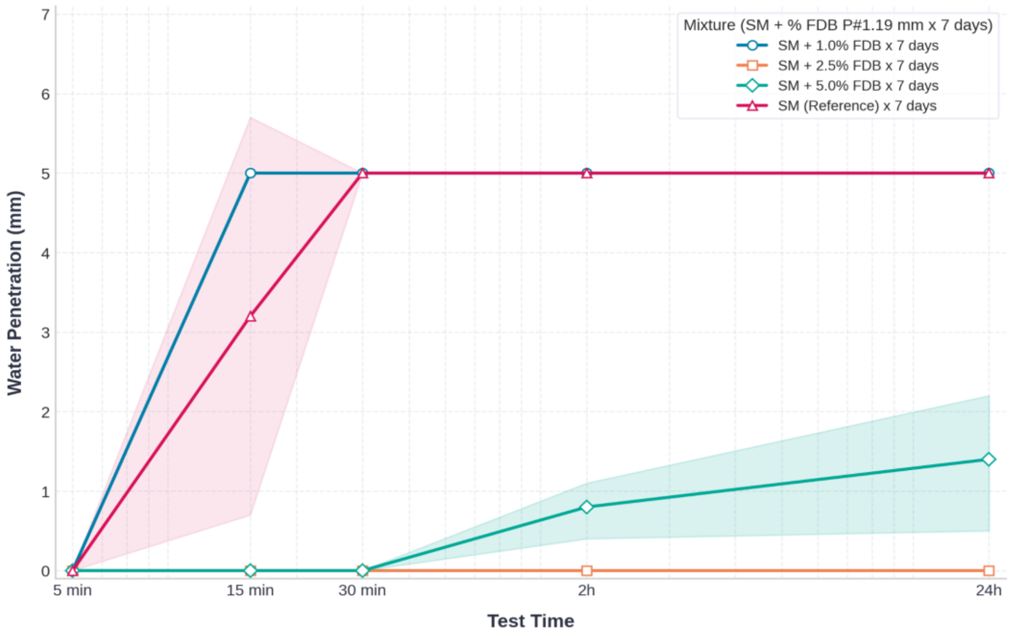


Source: Author (2026)

The introduction of Butia fibers (BF) showed results that vary substantially according to the content and curing time, as shown in Figure 3. At 7 days of curing, the mixtures with 1.0% and 2.5% BF showed rapid saturation, reaching 5 mm between 15 and 30 minutes, a performance similar to the reference soil. However, the 5.0% BF content at 7 days already demonstrated a notable improvement, keeping penetration below 2 mm even after 24 hours of immersion.

Figure 3

Water penetration as a function of time for soil + BF (7 days)

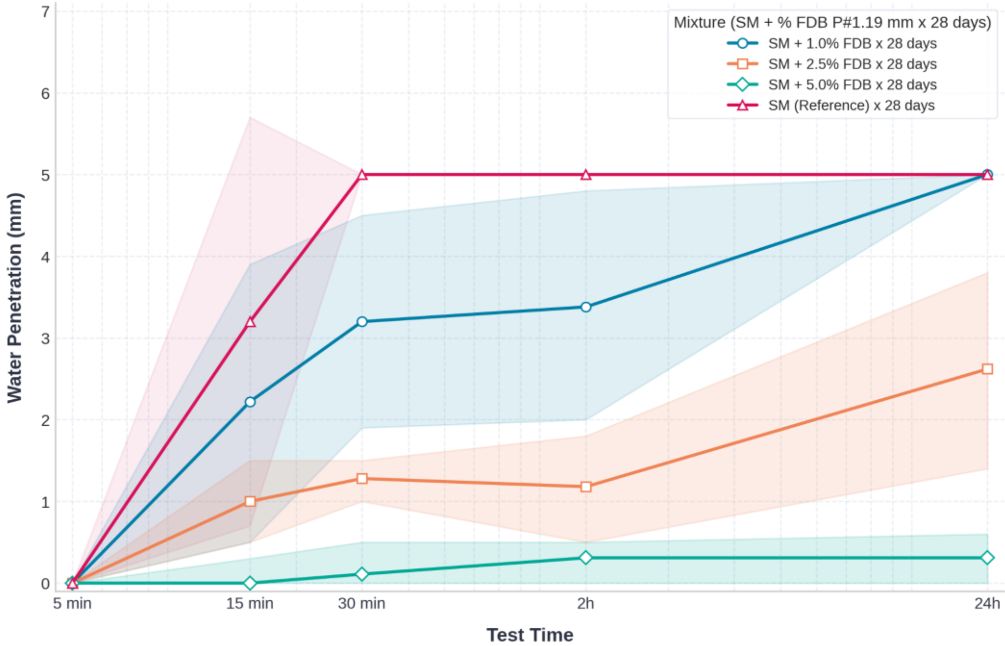


Source: Author (2026)

The most significant development occurred at 28 days of curing. At this stage, it was observed that the 5.0% BF network practically prevented severe water infiltration, maintaining penetration close to zero throughout the entire test (Figure 4).

Figure 4

Water penetration as a function of time for soil + BF (28 days)



Source: Author (2026)

Even the lower contents (1.0% and 2.5%) showed better retardation than that observed at 7 days, suggesting that the interaction time between the fibers and the soil matrix favors the system's stability. This indicates that the stress transfer bridge mechanism of the fibers not only provides mechanical reinforcement but also assists in maintaining the integrity of the specimens, hindering preferential water flow paths.

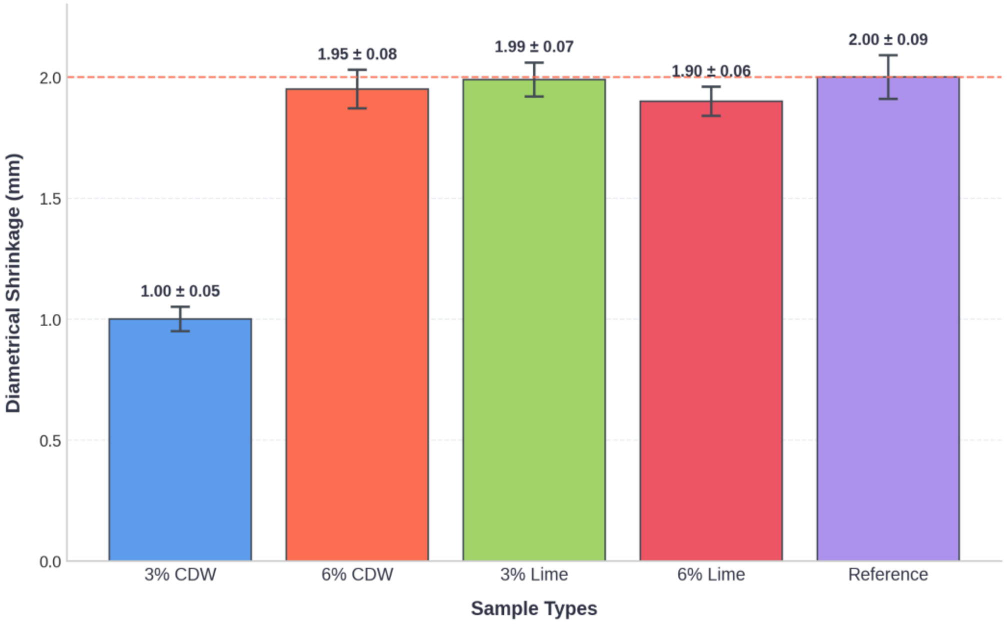
DIMENSIONAL STABILITY AND DIAMETRICAL SHRINKAGE

Diametrical shrinkage is a direct indicator of soil sensitivity to desiccation. While water penetration measures resistance to water entry, shrinkage assesses structural integrity when the soil loses moisture, allowing for the expeditious differentiation of the effectiveness of each stabilizing agent.

When analyzing conventional and recycled methods, it is observed that the reference soil presents an average shrinkage of 2.00 mm. The addition of 6% lime resulted in a discrete reduction to 1.90 mm, a value which, although indicating an improvement, demonstrates that chemical stabilization alone still allows for significant volumetric movement under severe drying conditions. Interestingly, the use of 3% CDW presented the lowest shrinkage value among the mineral methods (Figure 5), which suggests that the presence of recycled coarse aggregates can act as a physical skeleton that restricts the shrinkage of the clay mass, although, as seen previously, it does not prevent water infiltration.

Figure 5

Diametrical shrinkage graph for reference soil, lime, and CDW

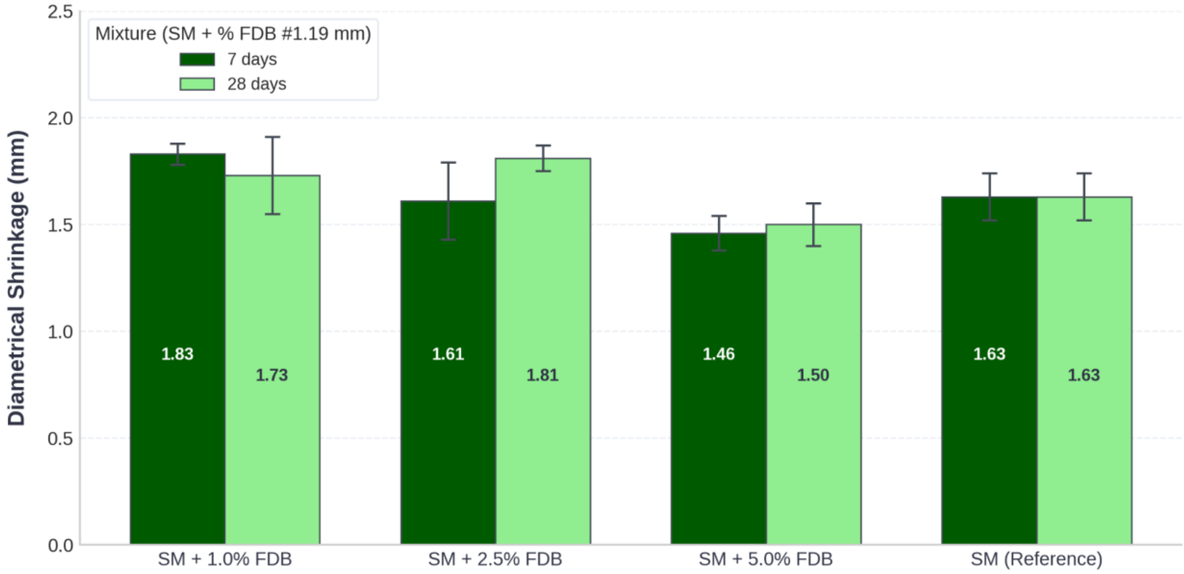


Source: Author (2026)

The introduction of Butia fiber brought a new dynamic to the dimensional stability of the system. Unlike lime, which acts on the mineral chemistry, the fibers act through mechanical anchoring. For the samples with BF, the shrinkage results ranged between 1.46 mm and 1.83 mm (Figure 6).

Figure 6

Diametrical shrinkage of mixtures with Butia fiber (7 and 28 days).



Source: Author (2026)

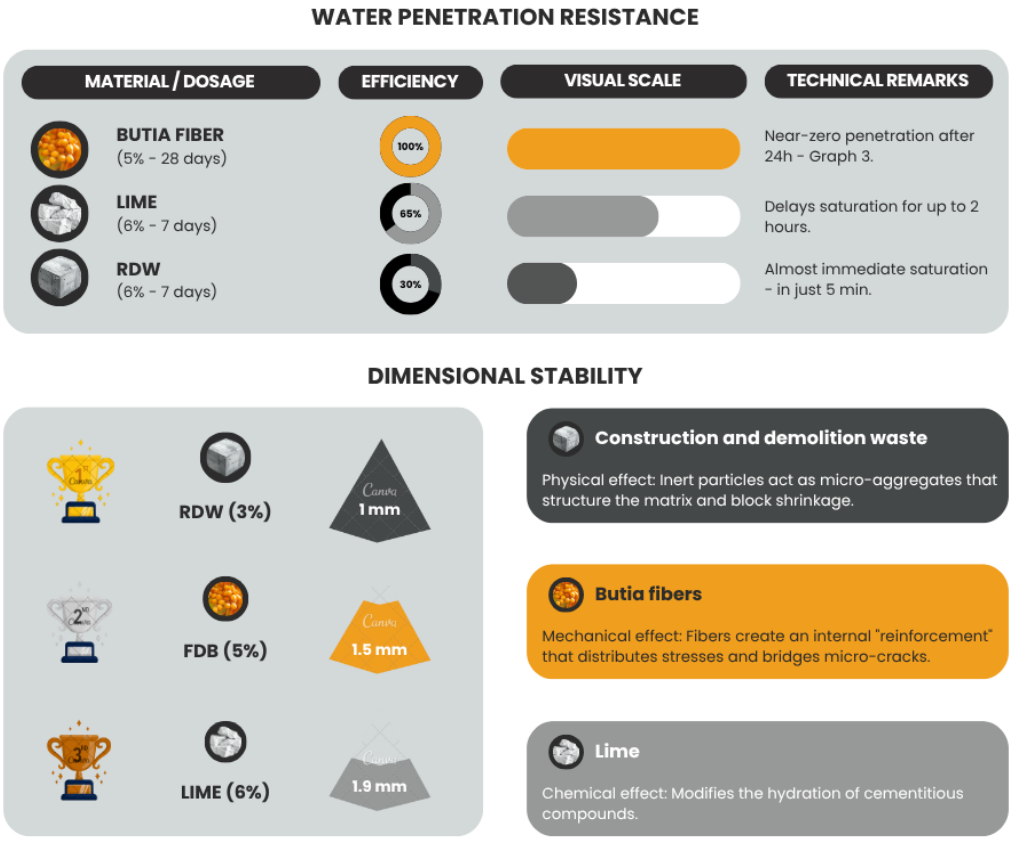
The best performance was observed at the 5.0% content at 7 days of curing (1.46 mm), indicating that a higher density of fibers in the matrix is capable of 'stitching' the soil more efficiently, reducing overall shrinkage compared to the natural soil.

A highlight is the maintenance of this stability at 28 days. Even with the expected natural variation in organic materials, the values remained consistent (around 1.50 mm for the 5.0% content), confirming that the Butia fiber network offers permanent physical restriction against tensile stresses generated by water loss. This capacity to keep the pellet intact, with less reduction in diameter, complements the excellent hydraulic performance observed previously, positioning the natural fiber as a multidimensional reinforcement agent.

To synthesize the findings of this study, Figure 7 presents a comparative analysis of the relative efficiency of each additive.

Figure 7

Relative Performance Infographic



Source: Author (2026)

It is evident that while lime and Butia fibers dominate in protecting against the advancement of the wetting front, CDW and fibers share the leading role in the physical restriction of diametrical shrinkage. This integrated view reinforces that Butia fiber acts as a hybrid agent, offering benefits that combine the best of chemical and physical stabilization.

DISCUSSION AND RESULTS

The comparative investigation between different stabilizing agents allowed for a clear overview of the technical efficiency and sustainable potential of each approach in mitigating the soil expansiveness in the region of Pelotas/RS. The results obtained consolidate the understanding that the choice of stabilizing material must balance mechanical performance, water resistance, and the environmental impact of the project.

Chemical stabilization with lime confirmed its historical efficacy, presenting a significant retardation of the wetting front and an improvement in dimensional stability, resulting from profound microstructural modifications. In contrast, the isolated use of CDW demonstrated severe limitations as a primary stabilizer, especially in controlling water infiltration, although it showed interesting behavior in restricting physical contraction due to its granular filling effect.

The major innovation of this study, the use of Butia fiber, positioned natural materials as a high-performance and low-impact alternative. Experimental data revealed that, with a content of 5.0% and a 28-day curing period, the natural fiber network was able to surpass the performance of lime regarding the blocking of water penetration, maintaining the integrity of the specimens for periods exceeding 24 hours. This behavior demonstrates that the stress transfer bridge, a mechanical effect of the fibers, not only reinforces the soil matrix against shrinkage cracks but also creates an efficient physical barrier against the advancement of the wetting front.

In summary, this chapter highlights that the transition from industrialized methods to solutions based on regional biodiversity, such as Butia fibers, is technically feasible and promising. For future large-scale applications, it is recommended to study the long-term biological durability of these fibers in the soil, consolidating the use of sustainable materials as a strategic pillar for contemporary geotechnical infrastructure.

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