ARAMID FIBERS AS PHYSICAL REINFORCEMENT AGENTS IN EXPANSIVE SOIL

https://doi.org/10.63330/aurumpub.031-013

Gustavo Luís Calegaro[1], Kelian Ramire Waskow Grellert[2], João Paulo dos Santos Simão[3], Ezequiel da Silva Tins[4], Rubiane Buchweitz Fick[5], Luís Eduardo Tavares Martins[6], Jessica Torres dos Santos[7], Jéssica Etcheverria do Prado Hartwig[8], Josiane Pinheiro Farias[9], Marcos Antonio da Silva[10], Rafael Miritz Bartz[11], Ana Clara Marins Mendes[12], Luiza Beatriz Gamboa Araújo Morselli[13], Thays França Afonso[14], Klaus Machado Theisen[15]

---

[1] Master's student in Environmental Sciences
Federal University of Pelotas
ORCID: https://orcid.org/0009-0004-7050-3129
[2] Undergraduate student in Environmental and Sanitary Engineering
Federal University of Pelotas
ORCID: https://orcid.org/0009-0003-7930-3281
[3] Undergraduate student in Control and Automation Engineering
Federal University of Pelotas
ORCID: https://orcid.org/0009-0005-1427-3215
[4] Undergraduate student in Civil Engineering
Federal University of Pelotas
ORCID: https://orcid.org/0009-0003-4850-6377
[5] Undergraduate student in Environmental and Sanitary Engineering
Federal University of Pelotas
ORCID: https://orcid.org/0000-0002-2131-4952
[6] Master's student in Environmental Sciences
Federal University of Pelotas
ORCID: https://orcid.org/0009-0008-6288-2412
[7] Master of Science in Environmental Sciences
Federal University of Pelotas
ORCID: https://orcid.org/0000-0002-6544-2286
[8] PhD candidate in Environmental Sciences
Federal University of Pelotas
ORCID: https://orcid.org/0009-0007-9296-0904
[9] PhD candidate in Materials Science and Engineering
Federal University of Pelotas
ORCID: https://orcid.org/0000-0002-8933-4984
[10] Master's student in Materials Science and Engineering
Federal University of Pelotas
ORCID: https://orcid.org/0000-0001-5372-1168
[11] Master's student in Water Resources
Federal University of Pelotas
ORCID: https://orcid.org/0009-0002-8732-6574
[12] Undergraduate student in Environmental and Sanitary Engineering, Federal University of Pelotas
ORCID: https://orcid.org/0000-0001-9580-7111
[13] PhD in Materials Science and Engineering
Federal University of Pelotas
ORCID: https://orcid.org/0000-0002-1703-7710
[14] PhD in Materials Science and Engineering
Federal University of Pelotas
ORCID: https://orcid.org/0000-0002-7803-7319
[15] Doctor of Civil Engineering
Federal University of Pelotas
ORCID: https://orcid.org/0009-0007-3689-7920

Robson Andreazza[16], Maurízio Silveira Quadro[17] and Rafael de Ávila Delucis[18]

Abstract

The stabilization of expansive soils, predominantly composed of smectitic clay minerals, is crucial in Geotechnical Engineering due to the critical behavior involving significant water absorption, volumetric deformations, and low bearing capacity. This applied research study investigated the effectiveness of incorporating aramid fibers into an expansive soil in the city of Pelotas/RS, taking advantage of aramid's properties of high tensile strength and chemical stability. The methodology, based on Atterberg limits tests and the Expedited Pellet Method (EPM), demonstrated that the fibers act as an efficient reinforcing agent. The addition of aramid promoted a reduction in the Plasticity Index (PI) to up to 10% (compared to 14% for the reference), suggesting an antiplastic effect restricting particle mobility. More significantly, the reinforcement drastically delayed post-cure water penetration by up to 300%, with the 1.5% fiber content registering only 0.7 mm of penetration after 24 hours. This performance is attributed to the formation of a three-dimensional network that acts as a hydraulic barrier, increasing pore tortuosity and mitigating diametrical contractions. In conclusion, the use of aramid presents promising technical effects in controlling soil expansion and plasticity, although its financial viability and the observed time-dependent behavior require caution and future studies.

Keywords: Synthetic fibers, Problematic soil, Soil stabilization, MCT, Geotechnics.

INTRODUCTION

Contemporary Geotechnical Engineering faces the persistent challenge of managing expansive soils, whose applicability in infrastructure projects is severely limited. This limitation is primarily

---

[16] Doctor of Soil Science
Federal University of Pelotas
ORCID: https://orcid.org/0000-0001-9211-9903

[17] Doctor of Soil Science
Federal University of Pelotas
ORCID: https://orcid.org/0000-0001-8236-7479

[18] PhD in Mining, Metallurgical and Materials Engineering
Federal University of Pelotas
Lattes: https://lattes.cnpq.br/0457288721496478

associated with their mineralogical composition, dominated by smectite-group clay minerals, particularly montmorillonite. The 2:1 crystalline structure of these minerals enables significant water absorption within the interlayer spaces, resulting in pronounced swelling behavior, volumetric instability, and reduced bearing capacity (CBR < 3%). Furthermore, variations in moisture content directly influence soil disintegration mechanisms and structural degradation, increasing susceptibility to erosion processes (Han; Wang, 2023). Consequently, the use of such materials in pavements, shallow foundations, and retaining systems becomes technically unfeasible without prior stabilization.

Stabilizing these soils is a technical imperative, and traditional methods, such as the incorporation of lime and cement, have historically been employed. However, the durability and environmental impact of these solutions, particularly in tropical regimes, have raised significant challenges (Díaz-López et al., 2023). In this context, geotechnical research has focused on sustainable alternatives, with emphasis on reinforcement with synthetic polymers, which combine technical efficiency with a lower ecological impact (Almajed et al., 2022).

One material that stands out in this scenario is aramid (poly(para-phenyleneterephthalamide)). Although its use is more established in geotextiles for environmental applications and in composite materials (Tanasă et al., 2022), its physicochemical properties make it an ideal candidate for direct reinforcement of the soil matrix. Aramid has high tensile strength (greater than 3 GPa), thermal stability above 400°C, and demonstrates remarkable resistance to hydrolysis in alkaline environments, maintaining approximately 80% of its original strength after 18 months at pH 9 (Derombise et al., 2011). Aramid fibers exhibit high mechanical strength, and their surface interactions can be enhanced by graphene oxide, increasing adhesion in polymer composites (Zhang et al., 2023). The performance of analogous synthetic fibers, such as polypropylene, has already indicated the potential of this reinforcement, with reductions of 35-40% in expansion pressure and increases of up to 65% in unconfined compressive strength (UCS) in treated soils (Syed et al., 2020). These results suggest that aramid, given its superior properties, may offer even more effective performance.

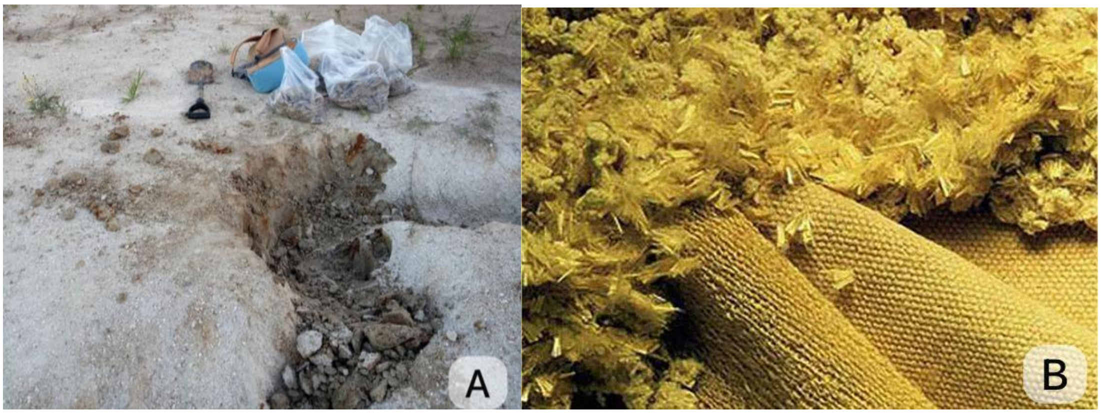
Given the scarcity of direct studies on the application of aramid in the stabilization of expansive soils, this study investigates the incorporation of aramid fibers into an expansive soil collected in Pelotas/RS. The objective is to evaluate the efficiency of the material in stabilizing and improving critical physical-mechanical properties, through standardized tests of Atterberg Limits (Liquid Limit - LL, according to ABNT NBR 6459/2016; and Plastic Limit - PL, according to ABNT NBR 7180/2016), and the Expedited Pellet Method (MCT) (Fortes et al., 2002; D'ávila, et al., 2008).

METHODOLOGY

The experiment used soil called "Quartier Soil (QS)", a clayey sand collected in Pelotas/RS (Figure 1A), whose fine fractions are known to be rich in smectite clay minerals. The expansive behavior and low resistance under wet conditions of this material have been previously reported in the literature related to the expedited method (D'ávila et al., 2008). The reinforcing agent used was Aramid (Kevlar®) supplied in pulp form (Figure 1B), with an average diameter of 12 µm and a cut length of 6 mm.

Figure 1

Image of the soil used (A) , Image of aramid (B)



Source: Authors, Kevlar® aramid fiber pulp. Source: DuPont (2026).

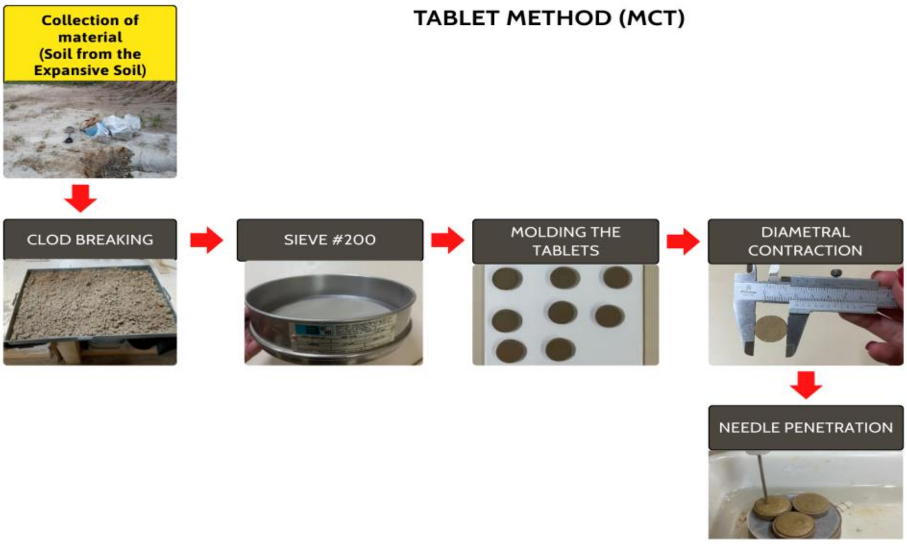
In the preparation phase, the soil clods were initially broken up in smaller pieces and dried in an oven at 60°C. To standardize the samples, the soil was separated into fractions passing through #40 mesh (for consistency limits tests) and #200 mesh (for the Expedited Pellet Method).

Aramid fibers were incorporated into dry soil at dosages of 0.5%, 1.0%, and 1.5% (by mass of dry soil). The mixtures were carefully homogenized while dry to ensure polymer dispersion before saturation. Performing the Atterberg limits of the mixtures was essential to evaluate it's plastic behaviour. To this end, consistency limits were determined in samples passing through a #40 mesh sieve, the liquid limit (LL) of the soil was determined using the casagrande apparatus, and the plastic limit (PL) was determined using the rolling method, following the procedures established in ASTM D4318 (2020). The results allowed the calculation of the Plasticity Index (PI).

The dimensional shrinkage and softening by water saturation behavior of the mixtures was investigated using the EPM, a procedure particularly relevant for tropical soils. The adopted protocol followed the guidelines of Nogami and Villibor (1994), in combination with the fifth approximation of the method proposed by D'Ávila et al. (2008). The material passing through the #200 mesh (0.075 mm) was selected for molding the tablets, as this fraction concentrates the clay minerals responsible for expansive behavior and maximizes the specific surface area and porosity of the samples. According to Abd Malik et al. (2023), finer particles create more interconnected pore spaces and exhibit higher water retention, which are critical factors for evaluating dimensional changes and softening upon saturation. The use of this controlled fraction ensures that the test results reflect the behavior of the active fine matrix, eliminating the interference of coarser particles. The soil was then saturated and spatulated until it reached the ideal molding point, defined by a 1 mm needle penetration. The tablets, with a diameter of 21.3 mm × H 5 mm in PVC rings, were then prepared and subjected to two distinct periods of open-air curing: 7 days and 21 days (Figure 2). The variation in curing time was established to monitor the development of interactions and the maturation of the soil-fiber composite, considering the time-dependent behavior inherent in many stabilized materials.

Figure 2

Tablet Method (MCT)



Source: Authors

After each curing period, the tablets were subjected to controlled drying in an oven at 60°C for 4 hours. Dimensional control was performed by measuring diametral shrinkage, providing an indicator of the shrinkage potential of the reinforced fine fraction of soil. The final and most critical test was the water reabsorption test, in which triplicate tablets were monitored. This test evaluated the resistance of the stabilized material to water intrusion, measuring needle penetration due softening, crack formation, and expansion behavior. The results of this stage are fundamental to determining the effectiveness of the aramid network in creating a hydraulic barrier and mitigating the reactivity of expansive clay minerals.

RESULTS AND DISCUSSION

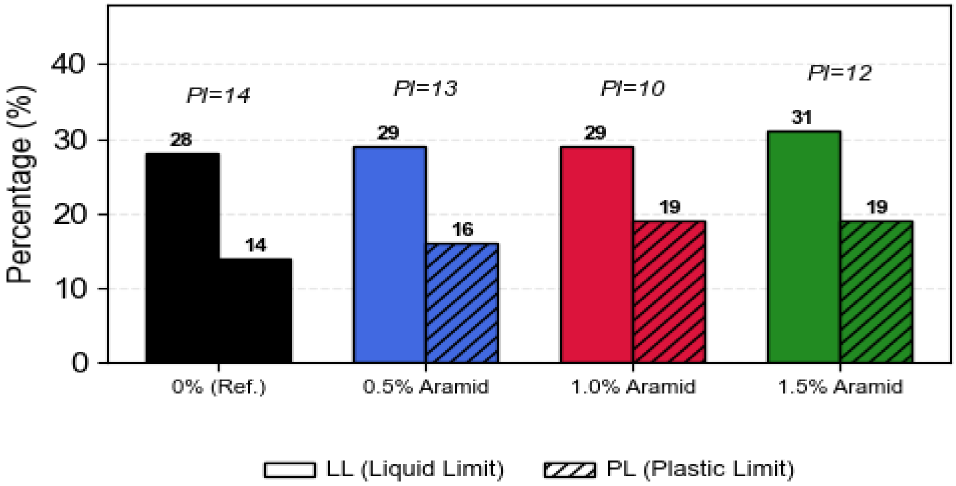
The analysis of consistency limits (Atterberg Limits), detailed in Figure 3, revealed a consistent trend in the modification of soil plasticity properties with the incorporation of aramid fibers. The results demonstrated that all aramid contents (0.5%, 1.0%, 1.5%) promoted a simultaneous increase in both the Liquid Limit (LL) and the Plastic Limit (PL) compared to the reference sample (0% Aramid).

The liquid limit (LL) in the mixtures ranged between 29% and 31%, exceeding the reference value of 28%, while the plastic limit (PL) showed notable increases, ranging between 16% and 19%, compared to 14% in the reference soil. This differential increase in limits culminated in a reduction of the Plasticity Index (PI), which went from 14% in the reference to values between 10% and 13% in the soils (soil + aramid). This trend characterizes a nonlinear plastic behavior as the aramid contents increase, evidenced by the gradual yet disproportionate decrease in the Plasticity Index (PI) with fiber incorporation (from 0.5% to 1.5%).

This behavior, which reached its maximum expression at a 1.0% aramid content with a PI = 10%, suggests an antiplastic effect resulting from the fiber-clay interaction. Aramid fibers appear to act as restrictive elements to particle mobility during saturation processes, possibly through the formation of modified capillary networks that limit water absorption and mobility, a promising result for the geotechnical stabilization of expansive soil.

Figure 3

Atterberg Limits (LL and LP) and the plasticity index (PI) of natural soil and mixtures with aramid.



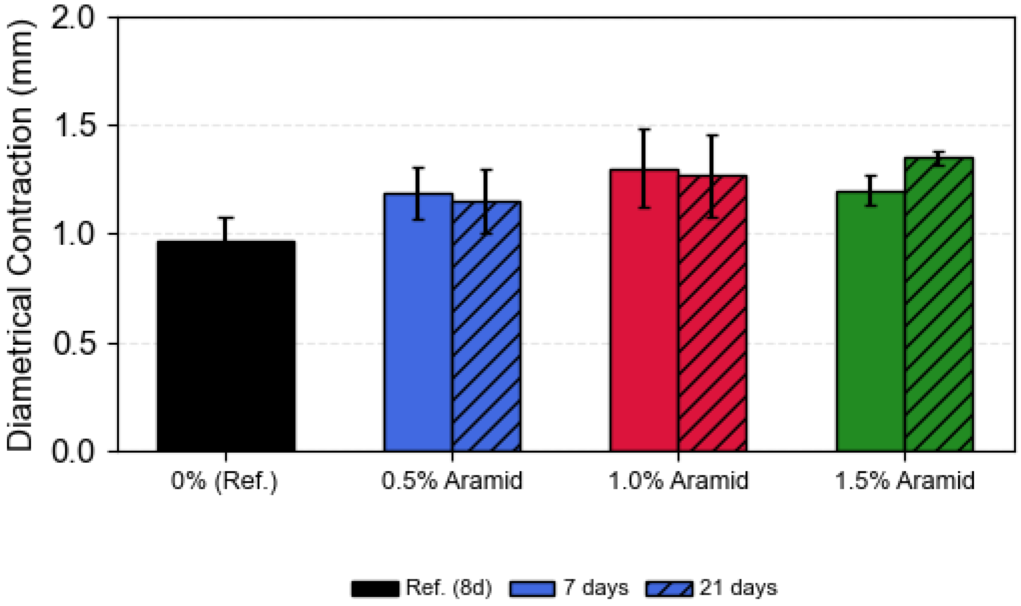
Source: Authors

Regarding dimensional behavior, Figure 4 illustrates the temporal pattern of diametral shrinkage of the specimens, an indicator of the soil's susceptibility to volumetric variations. Initially, after 7 days of curing, all soil-aramid mixtures exhibited diametral shrinkage values higher than that of the reference sample (0.97 mm), ranging between 1.19 mm and 1.35 mm.

After 21 days of curing, the evolution of shrinkage varied according to the fiber content. For the two lower contents (0.5% and 1.0%), the diametral contraction remained practically identical to the values observed at 7 days, indicating no significant evolution over time (1.15 mm and 1.27 mm, respectively). In contrast, the mixture with 1.5% aramid fiber showed an increase in shrinkage, rising from 1.20 mm at 7 days to 1.35 mm at 21 days.

Figure 4

Diametrical contraction of the tablets according to the curing periods.



Source: Authors

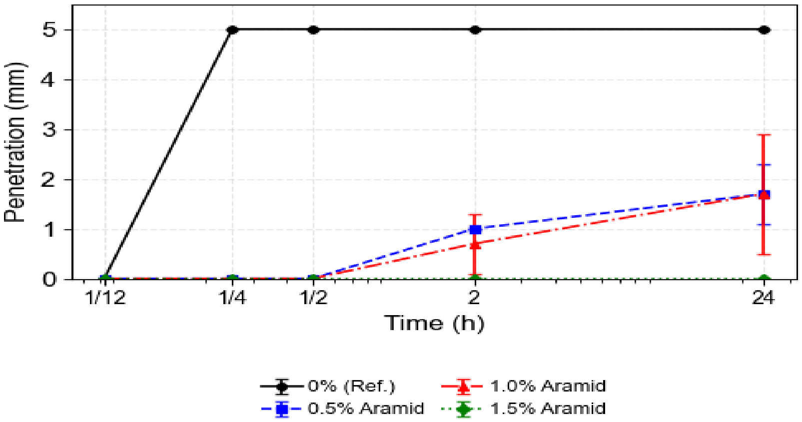
The diametral shrinkage observed in the tablets can be interpreted through the lens of the hornification process described by Mo et al. (2022) for cellulosic fibers. Although aramid fibers are not cellulosic, the concept of cocrystallization and pore crystallization offers a useful analogy. According to Mo et al. (2022), during the drying of cellulosic fibers, the removal of water leads to two distinct stages of irreversible structural changes: cocrystallization between adjacent microfibrils (at moisture contents between 70% and 31%) and crystallization of amorphous cellulose on pore surfaces (below 11% moisture). In the present study, the reduction in diametral shrinkage observed after 21 days of curing – particularly for the 1.5% aramid content, which decreased from 1.35 mm to 1.20 mm – suggests that the fibers act as physical restraints, limiting the collapse of the pore structure during drying. This effect is analogous to the second hornification period described by Mo et al. (2022), where pore crystallization leads to irreversible pore closure and increased structural rigidity.

The reduction in diametral shrinkage with increasing curing time is also consistent with the findings of Reis et al. (2024) for coir fiber-reinforced soils. The authors demonstrated that hornification – a treatment based on wetting-drying cycles – reduces fiber diameter, increases the aspect ratio, and improves fiber-matrix anchorage. In the present study, although aramid fibers are synthetic, their fine diameter (12 µm) and high aspect ratio (L/D = 500) promote effective interlocking with the clay matrix, restricting particle mobility during drying. Reis et al. (2024) also observed that fiber-reinforced composites exhibited reduced cracking and improved dimensional stability after prolonged exposure, which aligns with the enhanced performance of the 1.5% aramid mixtures after 21 days of curing.

The evaluation of standard needle penetration after water reabsorption, detailed in Figure 5, demonstrated the ability of aramid fibers to act as a hydraulic barrier and control reactivity to water.

Figure 5

Needle penetration as a function of water reabsorption time in the tablets after 7 days of curing.



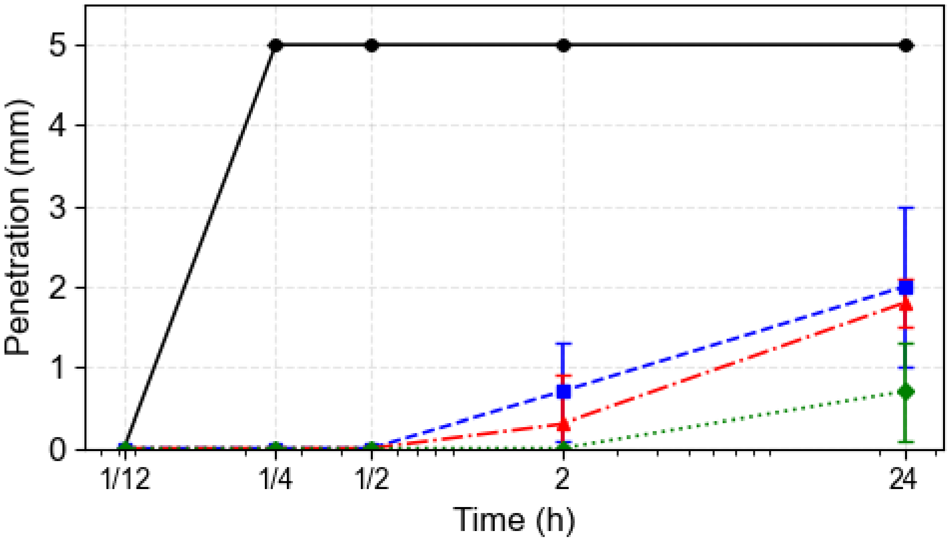
Source: Authors

In the analysis performed after 7 days of curing (Figure 5), the reference soil (0%) reached a total penetration of 5 mm in just 30 minutes of testing. In contrast, the soil-fiber mixtures showed significantly superior results. The mixture with 0.5% Aramid achieved only 1.7 mm of penetration after 24 hours, a performance 66% lower than the reference in the same time interval. The most notable performance in this period was from the 1.5% content, which maintained insignificant penetration (close to zero) after 24 hours.

With the increase in curing time to 21 days (Figure 6), the trend of water restriction was maintained and, in some cases, improved. The 0.5% content achieved 2.0 mm of penetration in 24 hours, but still remained 60% below the total penetration of the reference. The 1.5% aramid content maintained the best performance, registering only 0.7 mm of penetration.

Figure 6

Needle penetration as a function of water reabsorption time in the tablets after 21 days of curing.



Source: Authors

The observed evolution in needle penetration values may indicate a partial maturation of soil-fiber interactions, in which the fibers act as physical restraint elements against penetration stresses. However, the result also suggests the effect of fiber orientation in the tablets, a principle supported by physical-mechanical evidence in the literature.

The mechanism for reducing water penetration finds strong support in the literature. Al-Hosainat et al. (2023) demonstrated, in studies with cementitious composites, that fibers oriented perpendicular to the water flow reduce sorptivity by up to 35%. This occurs because the fibers create more tortuous paths, hindering water migration. This physical-mechanical principle is fundamental to explaining the results obtained with aramid. The fibers form a three-dimensional network in the tablet that acts as a hydraulic barrier, increasing the tortuosity of the pores and reinforcing critical interfaces. Consequently, the water restriction effect is analogous to the 20.8% reduction in chloride penetration observed in cementitious matrices with perpendicularly oriented fibers.

The delayed water penetration observed in the aramid-reinforced tablets after 7 days of curing can be partially explained by the pore-structure modifications associated with hornification-like mechanisms. Mo et al. (2022) reported that during the second crystallization period (moisture content below 11%), the crystallization of amorphous cellulose on pore surfaces leads to irreversible pore shrinkage and reduced water uptake. In the soil-aramid composites, the fibers appear to create a more tortuous pore network, hindering water migration. This is evident in the 1.5% aramid content, which maintained near-zero penetration after 24 hours, whereas the reference soil reached full penetration (5 mm) within 30 minutes. The effect is consistent with the formation of a hydraulic barrier due to increased pore tortuosity, as suggested by Mo et al. (2022).

The superior water resistance of the aramid-reinforced tablets after 7 days of curing is in line with the findings of Reis et al. (2024) regarding the improved performance of hornificated fibers. The authors observed that fibers with reduced diameter and enhanced surface adhesion contributed to better fiber-matrix interaction and reduced water absorption. Although aramid fibers do not absorb water, their high aspect ratio and uniform dispersion in the soil matrix create a dense network that physically blocks water pathways. Reis et al. (2024) also noted that fiber treatment significantly reduced the water absorption capacity of coir fibers, an effect that is analogous to the hydrophobic nature of aramid, which prevents water from penetrating the composite.

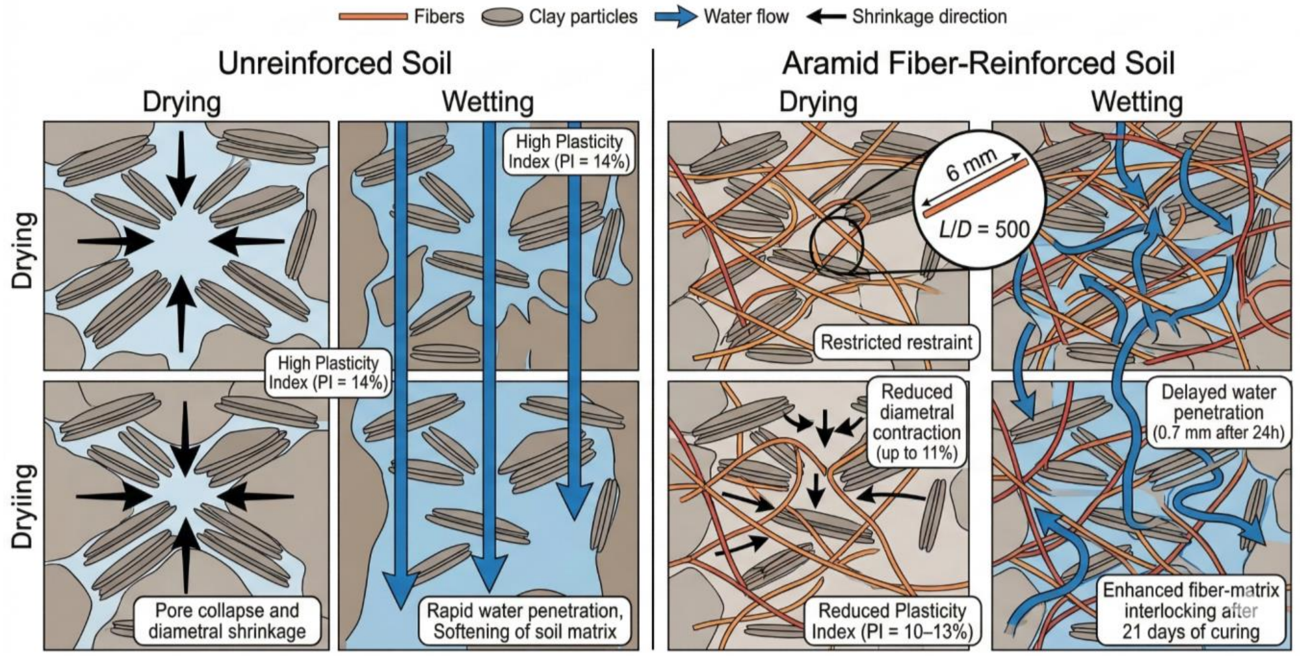
The further improvement in water penetration resistance after 21 days of curing suggests a time-dependent maturation of the soil-fiber interactions, which can be linked to the progressive development of irreversible structural changes, as described by Mo et al. (2022). In their study, prolonged drying led to increased crystallinity and pore closure, enhancing the material's resistance to rehydration. In the present case, the extended curing period may have allowed for the gradual formation of a more stable and less permeable fiber-matrix interface. The 1.5% aramid content, which exhibited only 0.7 mm of penetration after 24 hours, exemplifies this effect, indicating that the fiber network becomes increasingly effective as a hydraulic barrier over time.

The enhanced performance of the aramid-reinforced composites after 21 days of curing is consistent with the long-term behavior reported by Reis et al. (2024) for coir fiber-reinforced soils. The authors found that composites with hornificated fibers maintained their shear strength after five months of weathering, whereas untreated fibers showed significant degradation. In the present study, the prolonged curing period likely allowed for the maturation of interfacial bonds between the aramid fibers and the clay particles, resulting in improved resistance to water penetration. Reis et al. (2024) also emphasized the role of fiber aspect ratio and surface adhesion in maintaining composite integrity over time, which aligns with the superior performance of the 1.5% aramid content after 21 days.

The previous findings demonstrate that aramid fiber reinforcement significantly modifies the physical and mechanical behavior of expansive soils, reducing plasticity, limiting diametral shrinkage, and delaying water penetration. These improvements are attributed to the formation of a three-dimensional fiber network that increases pore tortuosity, enhances fiber-matrix interlocking, and restricts particle mobility during drying and wetting cycles. The underlying mechanisms can be understood through analogies with the hornification process described by Mo et al. (2022), where irreversible structural changes lead to pore closure and increased rigidity, and through the fiber-matrix interaction principles discussed by Reis et al. (2024), which emphasize the role of fiber aspect ratio and surface adhesion. To visually synthesize these concepts, Figure 7 presents a conceptual illustration comparing the microstructural behavior of unreinforced and aramid-reinforced expansive soils under drying and wetting conditions, highlighting the key reinforcement mechanisms discussed throughout this section.

Figure 7

Conceptual illustration of the reinforcement mechanisms provided by aramid fibers in expansive soil



Source: This figure was produced with the aid of Gemini generative AI and later revised by the authors to ensure technical consistency and scientific adequacy.

Left panel: unreinforced soil exhibiting high plasticity, pronounced diametral shrinkage, and rapid water penetration. Right panel: aramid-reinforced soil showing reduced plasticity, restricted shrinkage, delayed water penetration, and improved fiber-matrix interlocking after prolonged curing. The high aspect ratio of the fibers contributes to the formation of an effective three-dimensional network that acts as both a mechanical restraint and a hydraulic barrier.

CONCLUSION

The incorporation of aramid fibers into expansive soils has proven to be an effective strategy for enhancing their physical and mechanical behavior. The results demonstrated that the fibers reduced the Plasticity Index from 14% in the reference soil to values between 10% and 13%, with the optimal performance (PI = 10%) observed at 1.0% fiber content. Additionally, the fibers significantly reduced diametral shrinkage and delayed water penetration, with the 1.5% fiber content exhibiting the most pronounced improvements after 21 days of curing. These effects are attributed to the formation of a three-dimensional fiber network that increases pore tortuosity, restricts particle mobility, and enhances fiber-matrix interlocking. The time-dependent maturation of interfacial bonds further contributed to the composite's stability and resistance to rehydration. Although the findings suggest that aramid fibers offer promising technical benefits for controlling soil expansion and improving durability, economic feasibility and long-term field performance remain critical aspects requiring further investigation before large-scale application.

BIBLIOGRAPHIC REFERENCES

ABD MALIK, A. K. et al. Interpretation of soil grain size effect on electrical resistivity method. Physics and Chemistry of the Earth, v. 129, p. 103324, 2023.

ASTM INTERNATIONAL. ASTM D4318: Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils. West Conshohocken, PA: ASTM International, 2020.

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS (ABNT). NBR 6459: solo — determinação do limite de liquidez. Rio de Janeiro: ABNT, 2016. 5 p.

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS (ABNT). NBR 7180: solo — determinação do limite de plasticidade. Rio de Janeiro: ABNT, 2016. 3 p.

AL-HOSAINAT, Ahmad et al. Evaluation of the factors affecting the performance of fiber-reinforced asphalt mixtures. Journal of Materials in Civil Engineering, v. 35, n. 2, p. 04022435, fev. 2023.

ALI, Muhammad et al. Engineering properties of expansive soil treated with polypropylene fibers. Geomechanics and Engineering, v. 22, n. 3, p. 227–236, 2020.

ALMAJED, Abdullah; LEMBOYE, Kehinde; MOGHAL, Arif Ali Baig. A critical review on the feasibility of synthetic polymers inclusion in enhancing the geotechnical behavior of soils. Polymers, v. 14, n. 22, p. 5004, nov. 2022.

D'ÁVILA, A. M.; HAX, S.; FREITAS, P. C. Expedited specification of materials for unpaved roads – 4th approximation. In: XI CONGRESSO NACIONAL DE GEOTECNIA E IV CONGRESSO LUSO-BRASILEIRO DE GEOTECNIA, 4., 2008, Coimbra, Portugal. Anais [...]. Coimbra: [s.n.], 2008.

DEROMBISE, G. et al. Morphological and physical evolutions of aramid fibers aged in a moderately alkaline environment. Journal of Applied Polymer Science, v. 123, n. 5, p. 3098–3105, set. 2011.

DÍAZ-LÓPEZ, J. L. et al. Geotechnical and engineering properties of expansive clayey soil stabilized with biomass ash and nanomaterials for its application in structural road layers. Geomechanics for Energy and the Environment, v. 36, p. 100496, dec. 2023.

FORTES, Rita Moura; MERIGHI, João Virgilio; NETO, Alexandre Zuppolini. Tablet method for expedited identification of tropical soils. In: ROAD CONGRESS, 2., 2002, Lisboa, Portugal. Proceedings [...]. Lisboa: [s.n.], 2002.

MO, Wenxuan et al. Elucidating the hornification mechanism of cellulosic fibers during the process of thermal drying. Carbohydrate Polymers, v. 289, p. 119434, 2022.

NOGAMI, J. S.; VILLIBOR, D. F. Identificação expedita dos grupos da classificação mct para solos tropicais. Congresso Brasileiro de Mecânica dos Solos e Engenharia de Fundações. Anais...Abms, 1994.

REDDY, Peddireddy Sreekanth et al. Simultaneous evaluation of montmorillonite and Na/Ca content for assessing unstabilized and stabilized natural expansive soils for geoengineering applications. International Journal of Geosynthetics and Ground Engineering, v. 10, n. 6, p. 95, dez. 2024.

REIS, A. F. S. M. et al. Long-term behaviour of coir-fibre-reinforced soils. Geotextiles and Geomembranes, v. 52, n. 1, p. 1-14, 2024.

SYED, Mazhar et al. Stabilization of expansive clays by combined effects of geopolymerization and fiber reinforcement. Journal of The Institution of Engineers (India): Series A, v. 101, n. 1, p. 163–178, mar. 2020.

TANASĂ, Fulga et al. Geotextiles: a versatile tool for environmental sensitive applications in geotechnical engineering. Textiles, v. 2, n. 2, p. 189–208, abr. 2022.

ZHANG, Ziyi et al. Simultaneously enhanced interfacial shear strength and tensile strength of heterocyclic aramid fiber by graphene oxide. Nano Research, v. 16, n. 10, p. 12286–12293, out. 2023.