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Comparative Study of the Use of Green Coconut Fibre and Tyre Fibre in the Improvement of Expansive Soils in Paulista, Pernambuco, Brazil – Literature Review

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ABSTRACT: This study investigates, through a literature review, the behaviour of expansive soils treated with green coconut fibres and tyre fibres, aiming at stabilisation and reduction of problems caused by the expansiveness of these soils. The samples studied are from the municipality of Paulista, Pernambuco, a region characterised by the presence of expansive clays. Comparative tests reported in the literature were analysed to assess the influence of different fibre addition percentages (0%, 0.25%, 0.5%, 1%, and 2%) on soil expansivity and shear strength. The results indicate that the addition of green coconut fibres was significantly more effective in reducing the soil's 'free' expansion compared to tyre fibres. The inclusion of 1% green coconut fibre demonstrated a considerable reduction in expansivity and an increase in shear strength, making this proportion the most efficient for stabilising the analysed soil. On the other hand, tyre fibres, although also beneficial, required higher percentages (2%) to achieve comparable performance. This study highlights the potential of low-cost, sustainable materials, such as green coconut and recycled tyres, for the stabilisation of expansive soils, with applications in various regions where this type of soil occurs.

KEYWORDS: Expansive soils, green coconut fibre, tyre fibre, soil stabilisation, pathologies.

1 INTRODUCTION

Expansive soils present significant challenges in geotechnical engineering due to their high compressibility and low shear strength, exhibiting pronounced volumetric changes in response to moisture fluctuations. Swelling during wet conditions and shrinkage during dry periods can induce differential heave and settlement, adversely affecting structural stability and leading to substantial maintenance costs (JONES; JEFFERSON, 2012).

Population growth and accelerated urbanisation have intensified the generation of solid waste, among which scrap tyres stand out — in Australia alone, annual production exceeds 500,000 tonnes (SABERIAN *et al*., 2019). In the Brazilian context, green coconut accounts for approximately 70% of the waste found on beaches (ROSA *et al*., 2009), with the country ranking as the fourth largest producer worldwide, and the Northeast responsible for around 75% of national production (SILVEIRA; ARAGÃO, 2016; BNB, 2018).

In this context, this study explores the use of natural and recycled fibres, such as green coconut and tyres, as sustainable and low-cost solutions for the stabilisation of expansive soils, highlighting the variability in the effectiveness of these fibres according to local conditions and the proportions applied. Accordingly, the present research aims to assess the behaviour of expansive soils treated with green coconut fibres and tyre fibres, presenting a comparative analysis.

2 THEORETICAL FRAMEWORK

2.1 *Characterisation of the Region*

2.1.1 *Study Site*

The city of Paulista, Figure 1, situated approximately 20 km northeast of Recife, forms part of the Metropolitan Region and has a population of 300,466, with a population density of 3,087.66 inhabitants per km² (IBGE, 2010). Its coastline includes the beaches of Janga, Pau Amarelo, and Maria Farinha. Over the past fifty years, the city has undergone significant demographic growth, giving rise to various environmental challenges. Silva (2014) reports that 28% of the population lives in neighbourhoods near the beaches, while the coastal strip, extending for approximately 14 kilometres, contains residential areas, historical monuments, tourist facilities, and a cement factory.

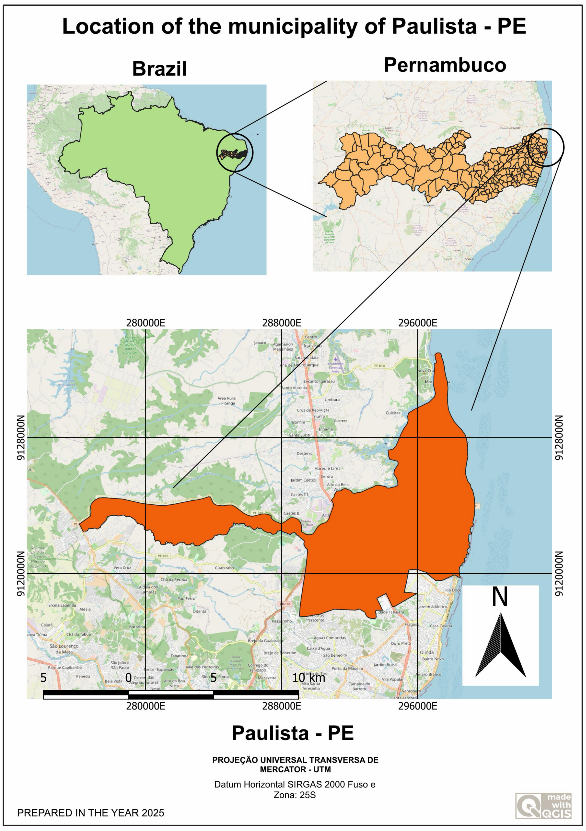

Figure 1. Location of Paulista in the State of Pernambuco, Brazil.

2.1.2 *Rainfall*

The climate of the municipality of Paulista, Pernambuco, Brazil, is characterised by its location at low latitudes and proximity to the Atlantic Ocean. The region experiences a humid tropical climate, with the most intense rainfall occurring between April and July. According to the National Institute of Meteorology (INMET, 2025), the average annual temperature is 26°C, with a thermal amplitude of 5°C throughout the year. The mean annual precipitation exceeds 1,700 mm, ranging between 1,000 and 2,000 mm/year (SILVA, 2014), as illustrated in the Climatic Normals chart for the period 1991–2020 in Paulista, PE, shown in Figure 2.

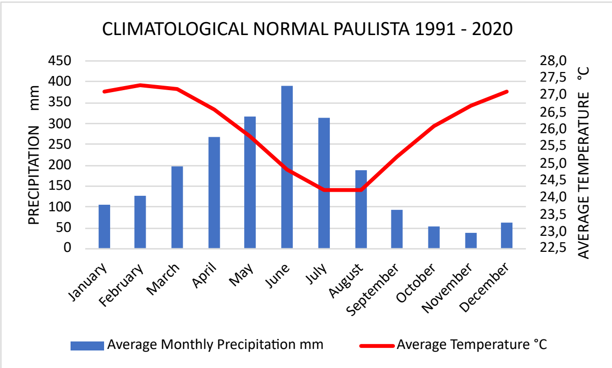

Figure 2. Climatological Normal Paulista 1991 - 2020.

2.1.3 *Soil Samples from Paulista, PE*

The disturbed soil samples were collected in the municipality of Paulista, Pernambuco, Brazil. The research on the improvement of expansive soils using green coconut fibres and tyre fibres was conducted at the Wastewater Treatment Plant (ETE) of the Pernambuco Sanitation Company (COMPESA), located in the Janga neighbourhood, in the southern region of the municipality, as shown in Figure 3.

Figure 3. Location of Disturbed Sample Collection (Faustino, 2022).

Research on the behaviour of soils in Paulista began in 1992, when Jucá *et al*. (1992) conducted analyses of expansive clay through laboratory and field tests. Subsequently, Bastos (1994) and Justino da Silva (2001) employed field instrumentation to assess the vertical displacement of the soil mass under various climatic conditions, characterising the active soil layer at depths ranging from 3.0 to 3.5 m.

2.2 *Expansive Soil Stabilisation*

The swelling of expansive soils represents a critical phenomenon in geotechnical engineering, being responsible for various structural damages. This study explores, through a literature review, the application of fibres to mitigate soil expansivity. Araújo (2023) emphasises that the effectiveness of fibres as reinforcement within a matrix fundamentally depends on the compatibility of the physical, mechanical, and chemical properties of the fibres with the matrix components, which may include soil, concrete, sandy concrete, or mortar.

2.2.1 *Green Coconut Fibres*

Green coconut fibres are obtained from the fruit of the coconut palm, a plant abundant in tropical regions, whose consumption has increased globally over the years. In Brazil, according to FAO data (2019), coconut production grew from 477,000 to 2.65 million tonnes between 1990 and 2016. Silva (2014) notes that, due to its low cost, availability, and abundance, coconut has experienced increasing market acceptance.

However, coconut husks are often considered waste, despite their still unexplored potential in production. Pimenta (2015) emphasises that the proper utilisation of coconut husks contributes to environmental preservation, as they take approximately eight years to decompose. Figure 4 illustrates coconut fibre as an environmental liability, being improperly discarded on beaches and streets.

Figure 4. Improperly Disposed on Beaches (G1, 2018 *apud* Faustino, 2022).

The processing of green coconut husks begins with their collection, followed by transportation and unloading at the processing facility, as shown in Figure 5.

Figure 5. Processing of Green Coconut, Adapted (Mattos *et al*., 2014).

2.2.2 *Tyre Fibres*

The tyre is described as an inflated rubber tube that fits onto the vehicle's wheel rim, providing traction and cushioning against impacts (ANDRIETTA, 2012). According to CONAMA Resolution (BRAZIL, 2009), new tyres show no signs of use or deterioration, whereas end-of-life tyres cannot be repaired due to structural damage. Chrusciak (2013) describes the components of tyres, including the tread, carcass, belts, bead, sidewalls, and overlay, all of which are essential for proper function. Figure 6 illustrates the main elements.

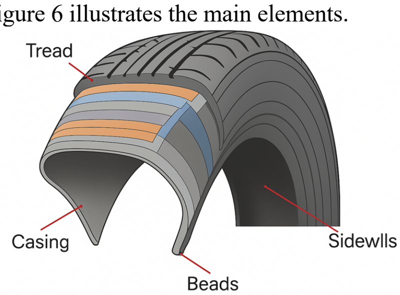

Figure 6. Components of the Tyre.

Tyres are composed of approximately 40% rubber, 25% petroleum derivatives, 15% steel, 5% fabrics, and 15% other chemical compounds (TAPAS; BALESHWAR, 2013 *apud* ARAÚJO, 2023). End-of-life tyres can be processed into various forms, such as chips, crumbs, fibres, and shreds, as illustrated in Figure 7. In civil engineering, these materials are commonly used as lightweight aggregates (EDINÇLILER, BAYKAL; SAYGILI, 2010).

Figure 7. Products from the Processing of End-of-Life Tyres (Edinçliler, Baykal e Saygili, 2010; Araújo, 2023).

Tyre fibres, by-products of retreading, have diameters ranging from 2 to 4 mm and lengths between 0.1 mm and 37 mm, free from textile materials or steel strips, making them suitable for soil-based compositions (EDINÇLILER; BAYKAL; SAYGILI, 2010).

2.3 *Locations in Brazil Identified with Expansive Soils*

Among the bibliographic references used in this review, the most studied soils were those from Pernambuco. Of these, the soil from the Paulista/PE region was the most frequently addressed, appearing in 40% of the studies, as illustrated in Figure 8. Subsequently, the soils from Ipojuca-PE accounted for 15% of the works, and those from Cabrobó-PE represented 10%.

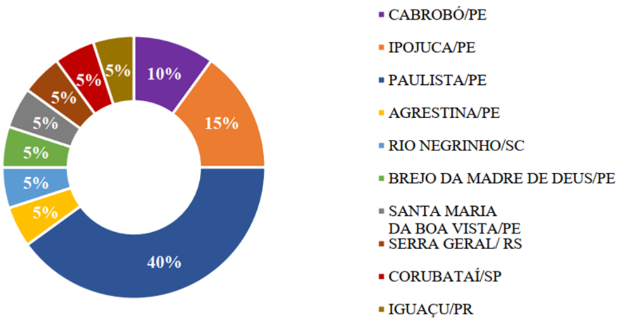

Figure 8. Percentage of Studies Conducted by Location (Varela *et al*., 2024).

Araújo (2023) emphasises that the effectiveness of fibres as reinforcement within a matrix fundamentally depends on the compatibility of the physical, mechanical, and chemical properties of the fibres with the components of the matrix, which may include soil, concrete, sandy concrete, or mortar. According to Paiva (2016), the semi-arid climate of Brazil is conducive to the formation of expansive soils. However, for this study, samples from the region located at the Wastewater Treatment Plant (ETE) of the Companhia Pernambucana de Saneamento (COMPESA) in the municipality of Paulista, Pernambuco, were analysed. Other areas studied in the literature are mainly in the states of São Paulo, Santa Catarina, Paraná, and Rio Grande do Sul, which are not part of Brazil's semi-arid region.

3 METHODOLOGY

This study aims to conduct comparative research. To achieve the proposed objectives, a qualitative approach was employed. In order to understand the issues related to the study area, an explanatory research design was applied. Within this context, the methodology involved analysing the behaviour of expansive soil with the addition of either green coconut fibres or tyre fibres, comparing the master's dissertations by Faustino (2022) and Araújo (2023), both from the Graduate Programme in Civil Engineering at the Federal University of Pernambuco. The two studies were carried out using soil collected from the same location in the municipality of Paulista, Pernambuco, Brazil.

4 RESULTS AND ANALYSES

4.1 *Selection of Mixture Proportions*

In both techniques, soil–fibre mixtures were prepared with fibre contents of 0%, 0.25%, 0.5%, 1% and 2%, expressed as a percentage of the dry weight of the materials involved. For green coconut fibres, the percentages were adopted based on the studies by Abbaspour *et al*. (2019), Kodicherla *et al*. (2019) and Mandeep *et al*. (2019) *apud* Faustino (2022), while for tyre fibres, the selection was guided by the research of Abbaspour *et al*. (2019) and Silva (2018) *apud* Araújo (2023).

4.2 *Physical Characterisation of the Soil*

Table 1 presents a summary of the physical characterisation of the natural soil from Paulista. The particle-size distribution test was conducted using sieving and sedimentation, employing sodium hexametaphosphate as a dispersing agent.

Table 1. Summary of the Soil Physical Characterisation.

SOIL	Faustino (2022)	Araújo (2023)
GRAVEL (%)	0	0
SAND (%)	31	35
SILT (%)	31	26
CLAY (%)	38	39
Liquid Limit	52,56	63,4
Plastic Limit	21,81	21,8
Plasticity Index	30,75	41,6
Specific Gravity of Solids (kN/m³)	26,7	26,7
Optimum Moisture Content (%)	21,3	23
Maximum Dry Unit Weight (kN/m³)	16,04	15,5
USCS Classification	CH	CH
AASHTO Classification	A-7-6	A-7-6

The soil samples were classified as the same type of soil, in accordance with the Unified Soil Classification System (USCS) and AASHTO standards.

4.3 *Characterisation of the Soil-Fibre Mixture*

Upon analysing Table 2, it can be observed that, for green coconut fibres, increasing the fibre content reduced the dry unit weight. This occurs because coconut fibre, being a lightweight material, replaces part of the soil, resulting in a decrease in the mixture's density. Another observed aspect is that the addition of fibres increased the optimum moisture content of the mixture. This increase can be explained by the formation of a thin water film around the fibres and soil particles, which requires more water to achieve optimal compaction conditions.

For the addition of tyre fibres, a tendency was observed for an increase in the maximum dry unit weight and a decrease in the optimum moisture content as the fibre percentage increased. These effects can be explained by the lower specific density, smaller surface area, and reduced water absorption capacity of the rubber particles compared to the soil grains. Thus, it can be concluded that the addition of tyre fibres primarily influenced the indices related to the soil's water content, notably reducing the liquid limit and, consequently, the plasticity index.

Table 2. Summary of the Physical Characterisation of the Soil–Fibre Mixture.

MATERIAL	Fiber Content (%)	Liquid Limit	Plastic Limit	Plasticity Index (%)	Maximum Dry Unit Weight (kN/m³)	Optimum Moisture Content (%)
GREEN COCONUT FIBERS	0,00	52,56	21,81	30,75	16,0	21,30
	0,25	58,70	25,11	33,59	15,8	22,80
	0,50	59,00	24,94	34,06	15,7	23,20
	1,00	64,50	25,92	38,58	15,5	23,90
	1,00	69,40	27,63	41,77	15,1	24,10
TIRE FIBERS	0,00	63,40	21,80	41,60	15,5	23,00
	0,25	56,22	28,32	27,90	15,7	23,50
	0,50	54,34	23,99	30,35	15,8	23,38
	1,00	52,67	20,94	31,73	15,9	22,60
	2,00	49,70	23,56	26,14	15,7	22,10

4.4 *"Free" Swelling and Swelling Pressure*

When comparing the results of the soil expansivity tests with the addition of green coconut fibre and tyre fibre, considering both "free" swelling and swelling pressure tests, the following points can be highlighted:

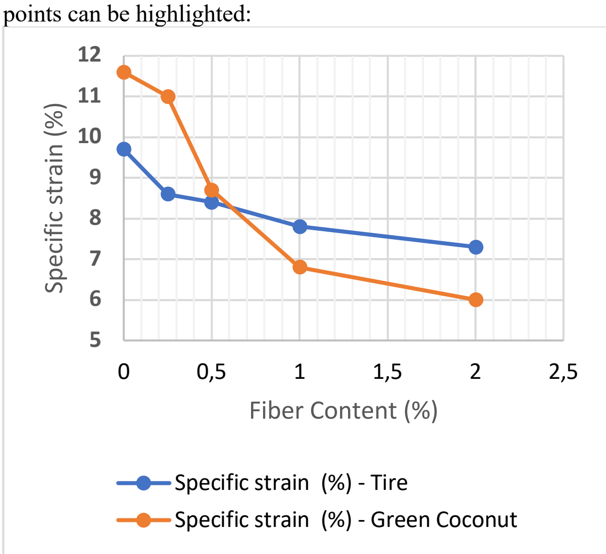

Figure 9. "Free" Swelling Results, Adapted from Araújo (2023).

Figure 9 illustrates the trend of decreasing specific deformation with increasing fibre content, both for coconut and tyre fibres. Data analysis reveals that green coconut fibres were far more effective in reducing the "free" swelling of the soil than tyre fibres. While a 1% content of green coconut fibres resulted in a considerable reduction, tyre fibres produced more modest decreases. Notably, the "free" swelling (%) under a pressure of 7 kPa exceeded 5% for all mixtures containing either green coconut or tyre fibres. According to the criteria established by Seed *et al.* (1962), which correlate "free" swelling with soil classification, the Paulista soil, even with the fibre contents and types analysed in this study, remains classified as highly expansive (ARAÚJO, 2023).

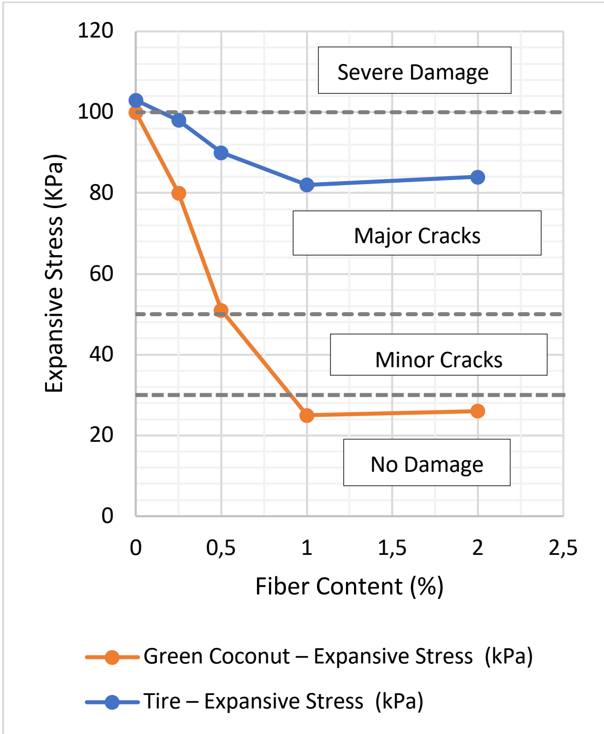

Figure 10. Results of Expansion Pressure.

In Figure 10, with the gradual addition of coconut fibres, a reduction in the tendency for cracking or structural damage is observed, progressing from Significant Cracks to Minor Cracks (0.5%) and reaching No Damage in the mixtures containing 1–2% fibres. Regarding the addition of tyre fibres, it can be seen that they influenced both the "free" expansion characteristics and the expansion pressure, leading to reductions in both as the fibre content increased. However, for all fibre contents used, the decrease in the degree of expansion was not sufficiently significant. Therefore, the soil, even with the presence of fibres, may still cause damage to structures built upon it.

However, it is important to highlight that the reduction in both "free" expansion and expansion pressure of the soil does not occur solely due to the addition of fibres, but also as a result of soil compaction. Therefore, to evaluate only the impact of the fibres, it is essential to compare the performance of compacted soil with and without the added material. Even with the fibre contents and types analysed in this study, the soil of Paulista continues to be classified as highly expansive (ARAÚJO, 2023).

4.5 *Direct Shear Test*

From the shear stress versus horizontal displacement curves, the Mohr-Coulomb failure envelopes are drawn, which in turn allow for the determination of the cohesion and internal friction angle of the soil and the soil–fibre mixtures. The corresponding values are presented in Table 3.

Table 3. Direct Shear Test Results for Different Fibre Contents.

MATERIAL	MIXTURE	Maximum Shear Stress (kPa)				Friction Angle (°)	Cohesion (kPa)
		50	100	150	200		
GREEN COCONUT FIBERS	Natural Soil	106	135	154	167	21	91
	Soil+0,25% fibers	107	118	142	164	21	84
	Soil+0,50% fibers	108	124	154	171	22	87
	Soil+1,00% fibers	112	133	154	177	22	91
	Soil+2,00% fibers	94	114	141	168	24	70
TIRE FIBERS	Natural Soil	111	135	154	167	21	95
	Soil+0,25% fibers	99	129	141	164	22	82
	Soil+0,50% fibers	104	118	128	146	15	90
	Soil+1,00% fibers	111	123	133	146	13	100
	Soil+2,00% fibers	106	140	155	180	25	86

For the green coconut fibre, a content of 1.00% incorporated into the expansive soil of Paulista-PE proved to be the most effective in increasing the strength of the naturally compacted soil at its optimum moisture content. Compressive, diametral tensile, and direct shear strengths all increased with the addition of coconut fibre. Furthermore, deformations at the point of failure increased as the amount of coconut fibre was raised.

For tyre fibre, the maximum shear stresses indicated that only samples with 2% fibre content achieved strengths comparable to or exceeding those of the natural soil. At a pressure of 50 kPa, this sample performed 4.55% lower than the natural soil, whereas at pressures of 100, 150, and 200 kPa, the results were 3.34%, 5.12%, and 7.23% higher, respectively. However, all other fibre percentages resulted in lower strengths.

Regarding the influence of fibre addition on soil strength, the best performance was observed in the soil mixed with 1–2% green coconut fibre. It should be noted that soil strength is influenced by multiple factors; the increase in strength parameters is not solely due to fibre addition but also to the soil compaction process. Therefore, to isolate the effect of the fibres, it is essential to compare the performance of compacted soil with and without the added fibres.

4.6 *Squeeze-flow*

For the mixtures with green coconut fibres and tyre fibres, the load versus displacement curves show no discontinuities, indicating good homogeneity between the tested material components. The three stages of the rheological profile were identified, with Stage I being considerably shorter than the other two. These results are presented in Table 4.

Table 4. Indices and rheological behavior data of the soil and mixtures at the LL. *W = moisture content; QESC = yield load; σEsc = yield stress; dEsc = yield displacement; εEsc = yield strain; QEnrij = initial hardening load (end of Stage II and beginning of Stage III); σEnrij = initial hardening stress (end of Stage II and beginning of Stage III); dEnrij = initial hardening displacement (end of Stage II and beginning of Stage III); εEnrij = initial hardening strain (end of Stage II and beginning of Stage III); QFinal = load for 8 mm displacement.*

MATERIAL	MIXTURE	Maximum Shear Stress (kPa)							
		w (%)	QESC (N)	σ ESC (kPa)	d ESC (mm)	QEnrij (N)	σ Enrij (kPa)	d Enrij (mm)	QFinal (N)
GREEN COCONUT FIBERS	Natural Soil	53	24	3,1	1,2	137	17	6,0	338
	Soilo+0,25% fibers	59	23	2,9	1,2	121	15	6,5	328
	Solo+0,50% fibers	59	22	2,8	1,8	99	13	7,0	298
	Solo+1,00% fibers	65	17	2,1	2,0	81	10	7,0	246
	Solo+2,00% fibers	69	13	1,7	3,0	72	9	7,0	227
TIRE FIBERS	Natural Soil	63	2	0,2	0,8	81	10	6,9	328
	Soil+0,25 % fibers	56	5	0,7	0,6	60	8	6,2	409
	Soil+0,50 % fibers	54	6	0,8	0,5	150	19	6,4	338
	Solo+1,00% fibers	53	7	0,9	0,4	180	23	6,3	333
	Solo+2,00% fibers	50	15	1,9	0,2	295	37	6,6	530

For the mixtures with green coconut fibres, both the yield stress (σ ESC) and the initial stiffening stress (σ Enrij) showed a decreasing trend as the fibre content increased. In contrast, the mixtures with tyre fibres exhibited the opposite behaviour. These phenomena may be related to the reduction of the liquid limit and the consequent decrease in soil moisture content as the amount of tyre fibres increases. This occurs because the soil's yield stress is directly influenced by the sample's moisture content and cohesion. On the other hand, in mixtures with green coconut fibres, the water content required to reach the liquid limit increases as the fibre content rises.

Thus, compared to green coconut fibres, tyre fibres result in a greater increase in both the yield stress and the initial stiffening stress relative to the natural soil.

5 CONCLUSIONS

This study aimed to evaluate and compare the behaviour of expansive soils treated with green coconut fibres and tyre fibres, with the goal of mitigating the effects of their expansivity, which can cause considerable structural damage. The soil samples analysed in this work were collected in the municipality of Paulista, Pernambuco, a region known for the presence of expansive clays.

The results showed that the addition of green coconut fibres was more effective in reducing the soil's 'free' expansion compared to tyre fibres. However, in both cases, the soil still exhibited a high degree of expansivity. The inclusion of 1% or more of green coconut fibres resulted in a significant reduction in expansion stress, allowing the soil to be classified as 'free from cracking damage'. On the other hand, tyre fibres, although they also contributed to reducing expansivity, were less effective, and the soil treated with them was classified as prone to "significant cracking".

Furthermore, the direct shear tests indicated that the addition of 1% green coconut fibre significantly increased the soil's shear strength, suggesting an improvement in the stability of the treated soil. In the case of tyre fibres, the highest shear strength values were observed only in mixtures containing 2% fibre, indicating that lower percentages were not as effective as green coconut fibres in enhancing soil strength.

This study highlights the potential of using natural and recycled fibres as a sustainable and low-cost alternative for the stabilization of expansive soils, particularly in regions with easy access to materials such as green coconut. However, it is important to emphasise that the effectiveness of fibres may vary depending on local conditions and the percentage of addition used.

For future research, more detailed investigations with different types of fibres are recommended, as well as long-term analysis of the stabilized soils, in order to assess their durability and strength under varying climatic and loading conditions.

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