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The fascinating complexity of seagrass bio-fibres: insights from bio-chemo-hygro mechanical analysis for their reuse as soil reinforcement

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ABSTRACT

Beached *Posidonia oceanica* seagrass fibres are an abundant yet underutilised Mediterranean biowaste with potential for sustainable reinforcement of cement-treated sediments. We present a first multiscale bio-chemo-hygro-mechanical characterisation, combining high-resolution synchrotron X-ray tomography with a 250 nm voxel size, FE-SEM/EDX, tensile testing, water-retention measurements. An image-based method links Aegagropile diameter to fibre length, enabling targeted selection of fibres in the 10–25 mm range to minimise clustering and favour reinforcing-network formation within the potentially-treated material. Air-dried fibres exhibit higher tensile strength, whereas pre-soaked fibres show greater porosity, tortuosity, ductility and toughness, and water-retention capacity, highlighting a moisture-dependent trade-off between strength and deformability. Water-retention curves reveal two storage domains: intra-fibre absorption within the lumen's porosity and capillarity in the inter-fibre pore space of bundled fibres. Within a cement-treated sediment mixture, 1% fibre addition does not significantly increase the unconfined compression strength, which is mainly governed by curing and cementation, but improves post-peak response, residual resistance, distributed cracking, ductility, and damage tolerance while maintaining comparable internal compactness. Ultrasonic pulse velocity results support that fibre inclusion does not compromise the internal compactness of the cement-treated sediment, while curing promotes progressive matrix densification. This dual mechanical and moisture-storage functionality positions *Posidonia oceanica* fibres as a circular bio-based reinforcement for cement-treated sediments.

1 Introduction

Improving the mechanical performance of soils and sediments and mitigating changes in their water content when interacting with the atmosphere are longstanding challenges in engineering science, now framed within the broader quest for environmentally sustainable solutions [1]. In recent years, research has increasingly focused on developing hydraulic binders that not only deliver high technical performance but also minimise environmental impact [2-4]. However, the mechanical behaviour of these mixtures is often limited by excessive brittleness and/or low strength. In this regard, the addition of synthetic fibres has been explored to enhance the materials' mechanical properties [5-9]. Recent studies on plant-derived fibrous networks (e.g., luffa sponge) demonstrate that reinforcement efficiency is governed by fibre architecture and network connectivity rather than fibre chemistry alone [10]. Most recently, the use of natural fibres has also been studied as a greener alternative. Among these, *Posidonia oceanica* (*P. oceanica*) has emerged due to its abundant availability along Mediterranean shorelines, presenting an opportunity to repurpose beached biomass that is typically destined for landfill, thereby coupling mechanical improvement with waste valorisation.

P. oceanica is a seagrass endemic to the Mediterranean basin and also found in the Southern Hemisphere, particularly in Australia [11-13]. Unlike algae, it is an aquatic plant with a complex organic structure. Over time, the decomposition of its rhizomes and sheaths leads to the formation of spherical *P. oceanica* fibre aggregates, known as Aegagropiles (*Figure 1a*), shaped by seawater movement [14, 15], variable in size up to a few centimetres (*Figure 1b, c*).

Despite their ecological and economic potential, approximately 5 million tons of *P. oceanica* leaves and Aegagropiles are collected annually along the Mediterranean coast. Yet, most end up in landfills, representing an underused resource and generating significant disposal costs [16]. Exploring ways to repurpose these fibres could provide environmental and economic benefits, and this is why multiple reuse options for *P. oceanica* have already been explored in the scientific literature, ranging from bio-based food packaging applications to the enhancement of mechanical performance in construction bio-composites [17-19]. Other natural fibres, such as straw fibres, have also been tested to improve the ductility of sediment-cement mixtures [20]. Synthetic fibres (e.g., polypropylene, polyvinyl alcohol) have been widely adopted to reduce soil hydraulic conductivity and to enhance shear strength and ductility [21-23]. In contrast, natural fibres, despite their intrinsic strength, low cost, wide availability, and environmental benefits, have received comparatively less attention in engineering applications, particularly for soil reinforcement. Existing studies on both artificial

and natural fibre reinforcement of cement and soil–cement mixtures consistently identify fibre length, content, and composition as key parameters governing mechanical performance [20, 24]. Notably, natural lignocellulosic fibres possess higher surface roughness and greater water absorption capacity than synthetic fibres, owing to their cellulose, hemicellulose, and lignin content [25]. Similar humidity-dependent structure–property relationships have been observed in other natural fibrous systems, where moisture alters fibre nanostructure and, consequently, mechanical performance [26]. Despite the growing interest in sustainable soil reinforcement, the hygromechanical behaviour of soils treated with natural fibres remains insufficiently understood. Among the possible candidates, *P. oceanica* appears to be one of the most promising but not sufficiently explored. Its potential for soil reinforcement lies in a unique combination of structural and chemical features: i) a high cellulose content (~40%), consisting of linear β -1,4-linked glucose polymers, which contributes to fibre cohesion and resistance to stretching through hydrogen bonding between adjacent hydroxyl (–OH) groups (Figure 1d) [27–29]. However, the tensile strength of natural fibres also depends on other multiscale factors, including microfibril orientation, fibre density, tubular morphology, lumen structure, and the amount of cellulose oriented along the loading direction; ii) a substantial lignin fraction (~30%), which enhances resistance to biodegradation and contributes to fibre coarseness, combined with hemicellulose (~22%) that binds cellulose polymers and reinforces the structure by improving water absorption capacity [30]; iii) a distinctive spatial arrangement in which a hemicellulose-rich outer layer protects a lignin-containing primary cell wall and inner cellulose-dominated layers; iv) a low salt content (0.5–2%), which increases stability against decomposition [14].

Considering these properties, this study systematically investigates the potential of *P. oceanica* fibres through a comprehensive multiscale bio–chemo–hygro–mechanical characterisation. Guided by an engineering perspective, the research identifies the key hygro-mechanical fibre properties that govern both their technical performance and practical effectiveness as reinforcement in soil mixtures, thus providing an original and consistent basis for their sustainable use in environmental engineering. Specifically, multiple aspects of *P. oceanica* fibres are examined. First, an image-based method is used to relate Aegagropile diameter to fibre length, providing a practical way to select suitable fibres and reduce clustering during mixing with treated sediments. Second, FE-SEM, EDX, and high-resolution synchrotron X-ray tomography are used to examine the fibre structure and composition, with particular attention to tubular morphology, lumen structure,

pore connectivity, and lignocellulosic composition [31]. Third, the effect of moisture condition is evaluated by comparing air-dried and pre-soaked fibres in terms of porosity, water content, water retention, tensile response, tortuosity, and toughness. Finally, the fibre-scale results are connected to the behaviour of fibre-reinforced cement-treated sediment through unconfined compression tests, failure mode observations, post-peak response, and ultrasonic pulse velocity measurements.

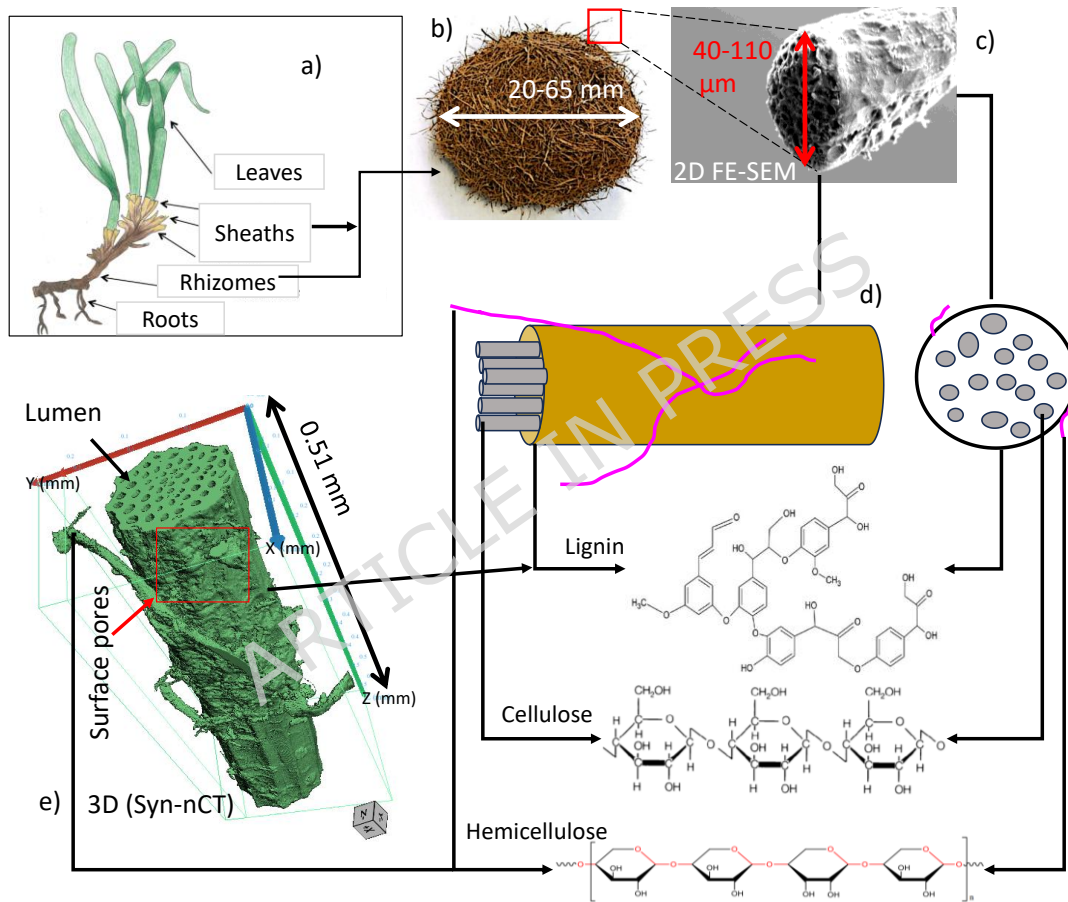


Figure 1: Microstructural features, schematic illustration, and molecular architecture of the natural *P. oceanica* fibre cell wall.

2 Results and discussion

2.1 Fibre length selection and clustering control

Fibre length optimisation and pre-conditioning are essential to prevent clustering effects. Long fibres tend to form clusters, while short fibres may fail to create an interwoven network [32], reducing their efficiency. When natural fibres are used for soil reinforcement, the issue of selecting the fibre length easily must be

considered. This is why we have developed a method to analyse fibre length from the average diameter of *P. oceanica* balls using image processing in both ImageJ and MATLAB. The characterisation has been carried out on twenty balls of different sizes of *P. oceanica* fibres previously air-dried, *i.e.*, left to dry under laboratory conditions (relative humidity of 50%) until equalisation before taking measurements.

The data reported in *Figure 2* reveal an evident correlation between *P. oceanica* ball diameters and average fibre length, showing a strong relationship in MATLAB using the longest skeleton path method ($R^2 = 0.95$) and in ImageJ with the bounding ellipse method ($R^2 = 0.78$) [33].

The same opening, scanning, and image-processing procedure was applied to all ball diameters to keep the comparison consistent. The lower correlation obtained with ImageJ is likely due to the limitations of the bounding ellipse method, which is less suitable for curved, bifurcated, or fragmented fibres. By contrast, the MATLAB skeleton-path method follows the fibre axis and allows branch pruning, giving a more realistic estimate of fibre length.

Figure 3 presents the normalised number of fibres for varying ball diameters, as obtained using the from-skeleton path technique in MATLAB. Fibres within the 10.1-15 mm and 15.1-25 mm length ranges increase in number as the ball diameter increases. The opposite behaviour is observed in fibres between 2.5 and 10 mm. In a broader context, upon selecting the most suitable fibre length from various ball sizes, the data show that ball diameters from 20 mm to 35 mm are more likely to correspond to the 2.5-10 mm length range (class 1), whereas the larger diameters are associated with higher probability of falling within the 10.1-25 mm length range (class 2).

Image analysis techniques have been demonstrated here to be efficient for automated estimation of fibre lengths. The results revealed a strong correlation between average fibre lengths and the diameters of *P. oceanica* balls. To the authors' knowledge, such a correlation has not previously been reported in the literature. This finding holds significant potential, as it can serve as a preliminary method for selecting balls to obtain specific fibre lengths tailored to the intended application. For instance, fibres in the 10–25 mm range were shown to provide optimal reinforcement in cement-treated dredged sediment, as they are more effective at forming an internal special grid and enhancing strength [34]. In this study, these insights guided the selection of fibre dimensions for the subsequent mechanical and hydraulic tests, performed on both separated and bundled fibres after manual separation. In particular, for the experimental investigation, ball diameters ranging

from 40 to 65 mm were selected to test only class 2 fibres, as this fibre-length range has been recognised as less affected by clustering when used as mechanical reinforcement in engineering applications.

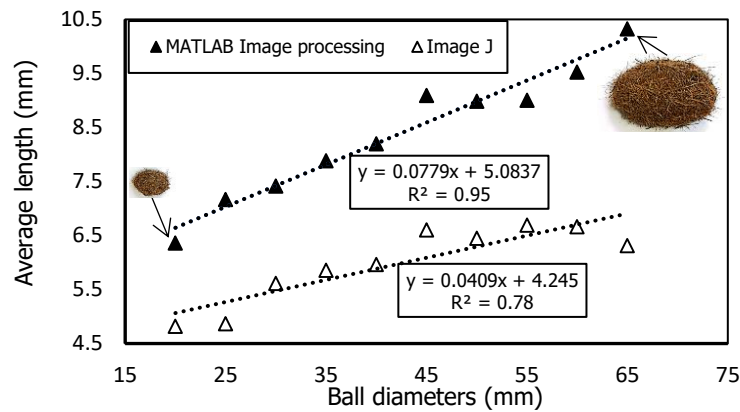


Figure 2: Correlation between the *P. oceanica* ball diameters and the length of the fibres.

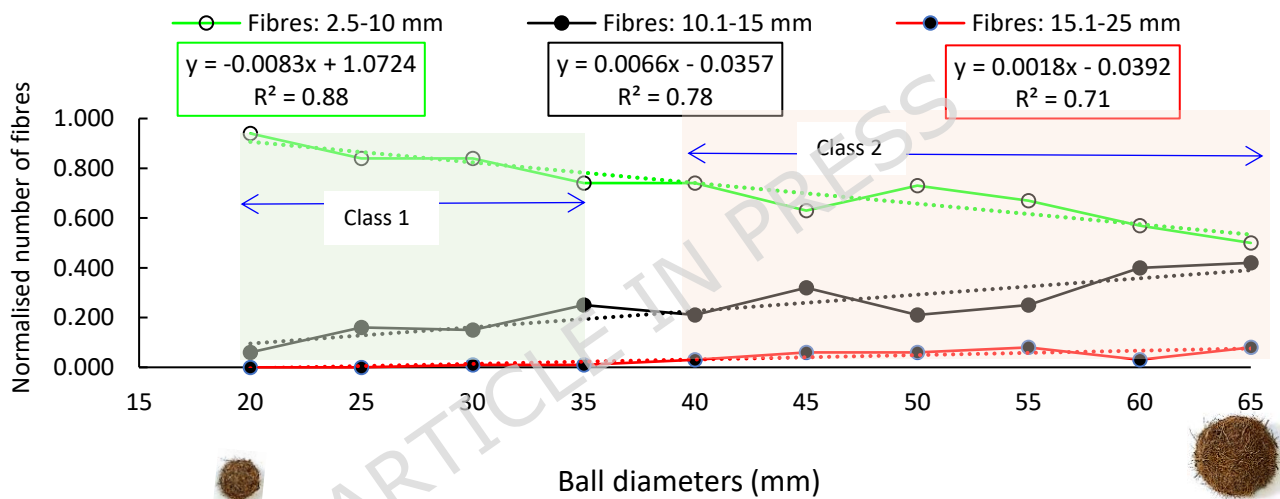


Figure 3: Correlation between the *P. oceanica* ball diameters and normalised number of the fibres and fibre classifications.

2.2 Microstructural and chemical features of *P. oceanica* fibres

The Field Emission Scanning Electron Microscope (FE-SEM) analysis of *P. oceanica* fibres shows a tubular-like morphology of the single fibres (Figure 4a) and the elemental analysis with Energy Dispersive X-ray (EDX) microanalysis confirmed that Carbon (38.6%) and Oxygen (44.3%) are the main components of the *P. oceanica*, followed by low contents of Sodium, Chlorine, Magnesium, Potassium, and Calcium (Figure 4b). Carbon and oxygen are homogeneously distributed throughout the fibre structure. These elements are primary constituents of biopolymers such as cellulose and lignin (Figure 4c).

The estimated atomic ratio of oxygen to carbon (O/C) is 0.86 (Section 3.3), indicating a higher proportion of cellulose relative to lignin. This aligns with previous studies reporting cellulose content at 40%

and lignin at 30% [11]. The composition is significant for understanding the mechanical response of the fibres. Cellulose content, crystalline microfibrils, and hydrogen bonding between hydroxyl groups contribute to fibre cohesion and resistance to stretching [28]. However, the macroscopic tensile strength of natural fibres is controlled by several multiscale factors, including microfibril orientation, fibre density, tubular morphology, lumen structure, and the amount of cellulose oriented along the loading direction. Meanwhile, lignin (~30%) contributes to controlled biodegradation [30].

The EDX images allowed observing the distribution of the main chemical components within the air-dried fibre, which is relatively homogeneous. Moreover, spots of Na and Cl are visible (*Figure 4c*), revealing localised zones of salt accumulation. This localisation can be attributed to several interacting phenomena. As water evaporates from the fibre's ends, through the lumen, the water menisci recede and concentrate at the centre of the lumen where localised salt precipitation is observed. Furthermore, drying can cause shrinkage of the fibre matrix, modifying pore geometry and connectivity (discussed in Section 2.2.2). The observed NaCl clustering thus reflects the combined effects of capillary flow, solvent redistribution during the drying process, fibre shrinkage, evaporation-induced supersaturation, and precipitation process.

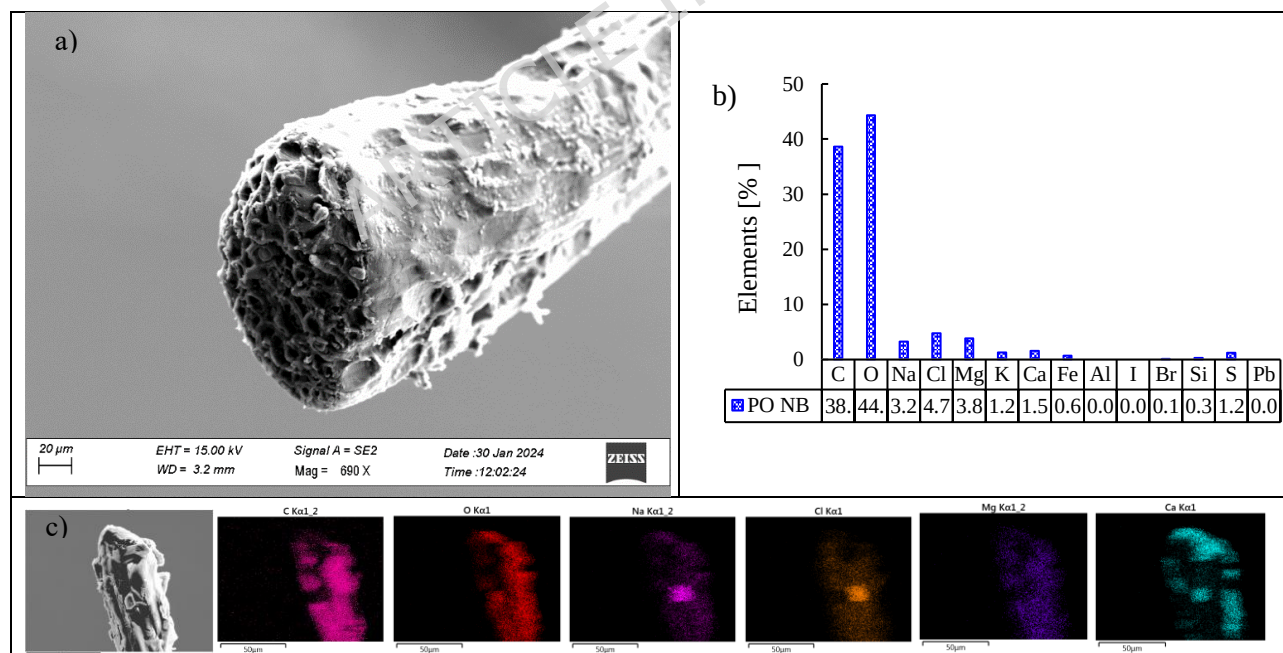


Figure 4: a) Cross-section FE-SEM image of a single P. oceanica fibre, b) elemental composition of P. oceanica fibres obtained from EDX; and c) EDX image analysis of P. oceanica fibres with colour mapping.

3D synchrotron X-ray tomography with nanoscale voxel resolution (Syn-nCT) was conducted at the ID16B beamline of the European Synchrotron Radiation Facility (ESRF) (*Figure 5a*) on both air-dried (AD) and pre-soaked (PS) fibres. The pre-soaked condition was achieved by immersing the fibres in seawater for 48

hours. After soaking, the fibres were gently placed between filter papers for 60 s to remove most of the excess surface water (not retained in pores), following a procedure equivalent to the standard described in [35].

The fibres were placed in 0.3 mm-diameter borosilicate glass quartz capillaries (*Figure 5b*) and sealed with grease to prevent moisture loss (*Figure 5c*). Then, image stacks were acquired and subsequently reconstructed, see Section 3.4 for details. As a result, high-resolution images of the fibres were obtained (*Figure 5d*).

Figure 6a, b shows the 3D rendering of the hollow tubular structure and internal open channels within the fibres. The visualisation highlights variations in pore diameter and shape, with different colours representing specific pore sizes and morphologies. Such three-dimensional synchrotron-based analyses enable reliable quantification and interpretation of nanoscale voxel resolution pore networks and lumen connectivity in fibrous porous materials [31]. Compared to conventional laboratory-based microscopy techniques, synchrotron X-ray tomography uniquely combines high spatial resolution, a large field of view, and non-destructive three-dimensional imaging, making it particularly suitable for analysing heterogeneous geomaterials and cement-related systems [35]. The segmentation and 3D rendering highlight the presence of pores and fissures between the tubular structures (*Figure 6c*), thereby increasing the AD fibres' pore connectivity. For the PS fibres (*Figure 6d*) significant reduction in pore connectivity between the lumens can be observed, with fewer fissures.

These structural differences suggest distinct porosity characteristics between AD and PS fibres. Accordingly, the subsequent analysis focuses on quantifying and comparing their porosity to elucidate the influence of microstructural variation on fibre hygromechanical performance.

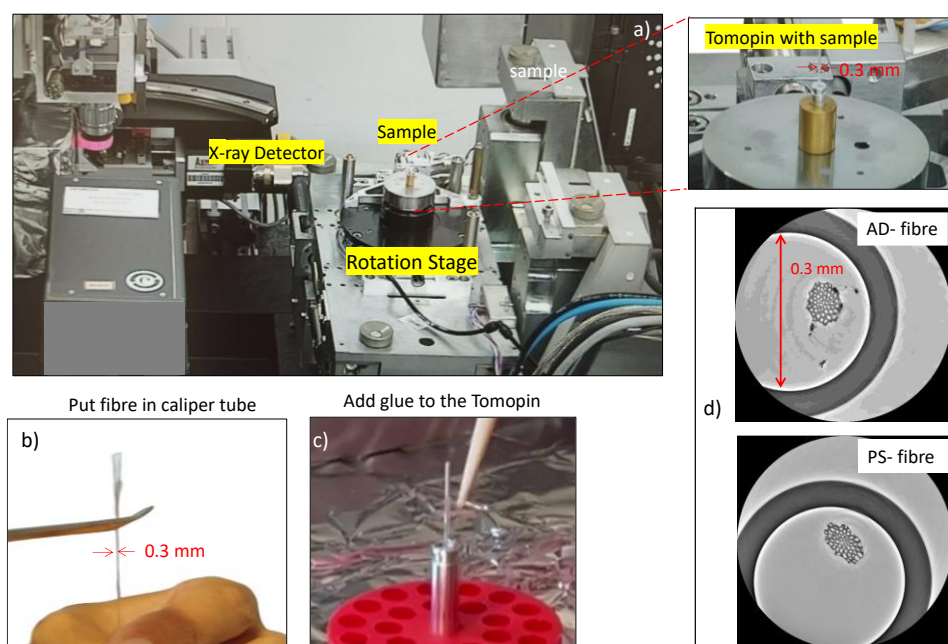


Figure 5: a) Setup for Syn-nCT at the ESRF; b) and c) sealed borosilicate glass quartz capillary; d) high-resolution images of AD and PS fibres.

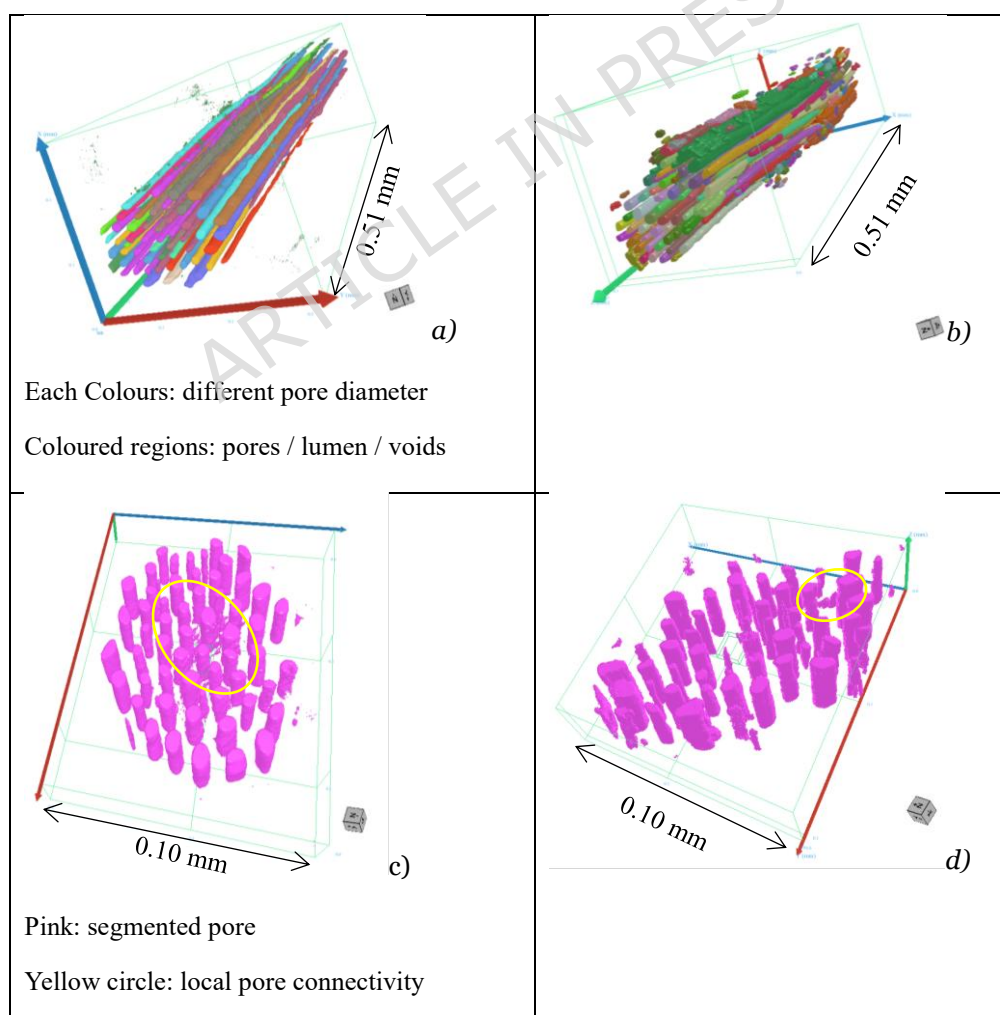


Figure 6: Syn-nCT 3D rendering of the segmented pore/lumen network: a) air-dried fibre, b) pre-soaked fibre, c) pore connectivity in the air-dried fibre, and d) pore connectivity in the pre-soaked fibre.

The porosity was calculated using 2D and 3D approaches on the X-ray tomography images. Porosity (n) is defined as the ratio between void volume (V_v) and total volume ($V_t = V_v + V_s$), where V_s represents the volume of solids in the fibre. Discrepancies were observed between 2D and 3D porosity measurements (0.248 versus 0.194 for AD and 0.271 versus 0.217 for PS fibres, respectively). Therefore, the diameter–length correlation is considered a practical fibre-selection criterion rather than a complete representation of the full fibre-length population, as 2D imaging inherently cannot provide accurate volumetric porosity measurements, as porosity is a three-dimensional property that requires 3D analysis for more precise quantifications. These results quantify the magnitude of error that can occur when relying solely on 2D measurements for a fundamentally three-dimensional property such as porosity. The 11–12% higher porosity measured by 3D Syn-nCT analyses for PS fibres compared to AD fibres is likely due to water absorption, which swells the fibres and expands the internal pore structure, enhancing the water retention capacity. This phenomenon, already described by [36], is influenced by factors such as cell wall composition, pore connectivity, and fibre-water interactions, all of which affect the hygromechanical properties of the fibres.

2.3 Moisture-dependent tensile response of *P. oceanica* fibres

When treated with binders or cements, soils tend to become more brittle [37]. Incorporating fibres in the mixture is a possible way to enhance tensile strength and to mitigate brittle failure by promoting a ductile response. To assess the efficacy of *P. oceanica* fibres in this respect, tensile tests have been conducted on AD and PS fibres, and their mechanical performance has been explored. The tests were carried out according to ASTM C1557–03 [38] in a TA HR30 Discovery Hybrid Rheometer. Each fibre was mounted in a paper frame using adhesive [39] and subsequently secured in the clamp of the tensile testing apparatus (*Figure 7a,b*).

Figure 7c shows the tensile test results of two AD and two PS fibre specimens (see the tensile stress calculation in Section 3.5). Generally, the results seem to be consistent with each other. A broad observation is that AD fibres, on average, exhibit a higher tensile stress than PS fibres, but with lower ductility. Similar moisture-induced structure–property relationships have been reported in other natural fibrous systems, where increased humidity alters fibre nanostructure and leads to a trade-off between tensile strength and toughness [26, 40, 41]. From the test results reported in *Figure 7d*, toughness values, the ability to absorb energy per unit

volume and plastically deform without breaking, of about 400 and 1000 kJ/m³ are calculated for AD and PS fibres, respectively. These results align with those obtained from other natural fibres and plant roots [42].

As reported in *Table 1*, the morphological tortuosity values derived in MATLAB, which express how twisted the fibre is (actual fibre length) in relation to a straight-line distance between endpoints, show that PS fibres exhibit a higher initial average tortuosity, compared to AD fibres. Therefore, the higher strain at failure (*Figure 7c*) of PS fibres are the result of two different contributions to the global strain, *i.e.*, a geometric and a constitutive one. First, the higher tortuosity of PS fibres contributes to their higher ‘geometric’ component upon alignment of the twisted fibre. Second, water enhances plastic deformation, allowing the fibres to stretch more easily and increasing their constitutive strain component. Therefore, both components, geometric alignment and plastic stretching, contribute to the overall deformation. To better highlight this issue, *Figure 7d* represents the strain at failure ε_s for individual fibres (both AD and PS) resulting from geometric alignment and plastic stretching, normalised by the lowest strain at failure ε_d observed for AD fibres. As shown in *Figure 7d*, the higher is the tortuosity, the larger is the normalised strain at failure in the fibres.

This geometric alignment and plastic-stretching effects are further evidenced by the increase in toughness and lower secant Young modulus (evaluated between the axial strain values: $\varepsilon = 27.03\%$ and $\varepsilon = 28.52\%$) of PS fibres (*Table 1*), which reflects reduced stiffness as determined from the slope of the line from zero to the point at half the failure strain on the stress–strain curve.

Since the number of valid tensile tests is limited, the tensile data are not intended to represent the full natural variability of the fibre population. However, the results provide useful mechanistic insights into the moisture-dependent response of individual *P. oceanica* fibres. Within such limitations, the valid specimens showed a consistent response: air-dried fibres exhibited higher tensile strength and stiffness, whereas pre-soaked fibres showed greater ductility, tortuosity, and toughness (*Figure 7c, d*). This behaviour could suggest that fibre–water interaction influences the single-fibre mechanical response, with drying favouring tensile strength, while pre-soaking enhancing deformability and energy absorption through geometric alignment and water-assisted plastic stretching.

Table 1: Morphological and tensile parameters of valid AD and PS P. oceanica fibres used in the single-fibre tensile tests.

	Specimen	Volume (mm ³)	Diameter (mm)	Tortuosity (-)	Strain at failure (%)	Toughness (kJ/m ³)	Secant Young modulus (GPa)
AD fibre	AD-S1	0.0582	0.0997	1.030	7.50	454	1.83
	AD-S2	0.0632	0.1049	1.012	8.30	399	1.36

PS fibre	PS-S1	0.0457	0.0890	1.307	27.0	921	0.27
	PS-S2	0.0393	0.0766	1.180	28.5	1100	0.29

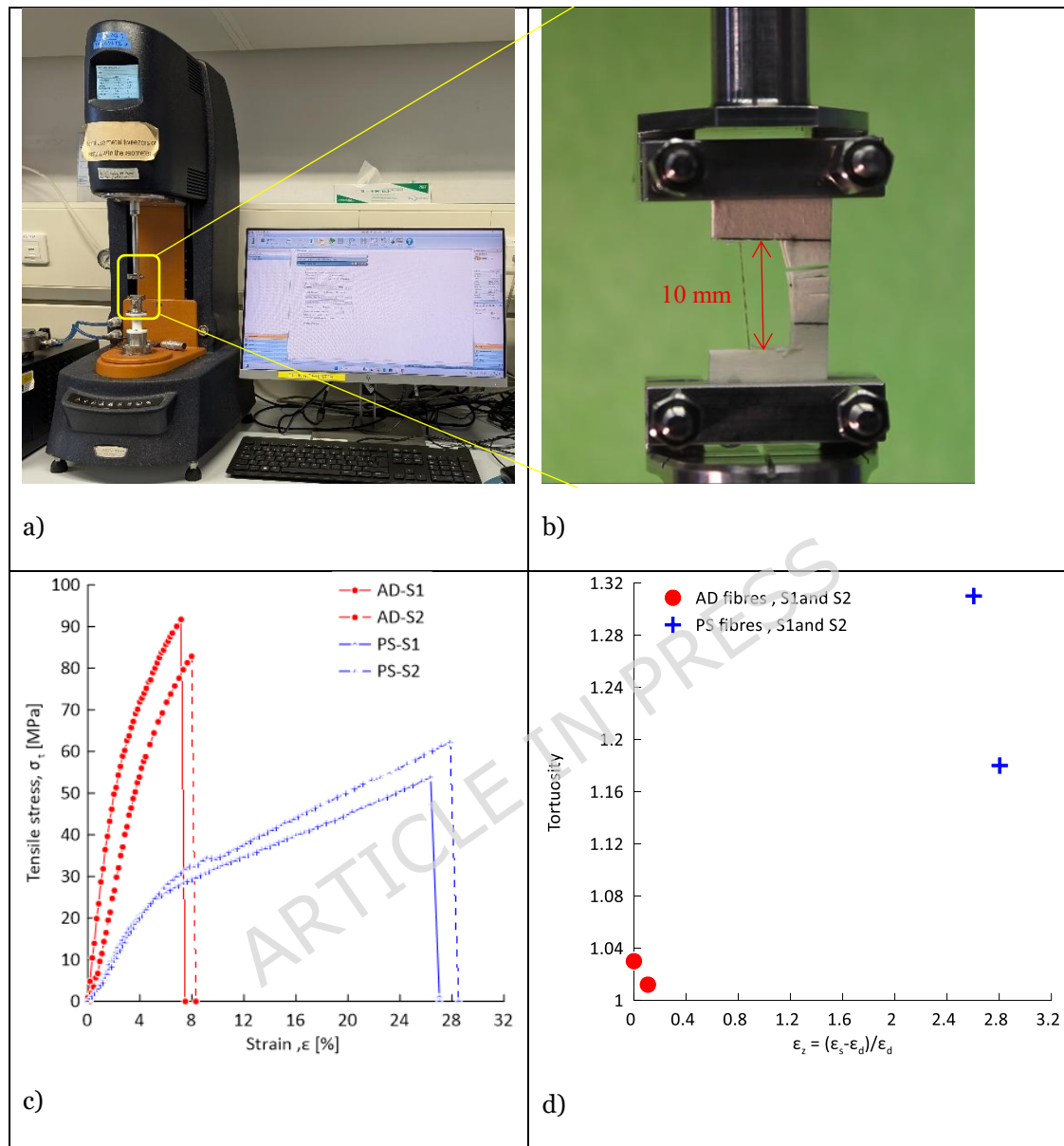


Figure 7: a) Single fibre tensile test setup; b) fibres within a paper frame and clamp; c) tensile test results; and e) correlation between tortuosity and the normalised strain at failure with respect to AD fibres.

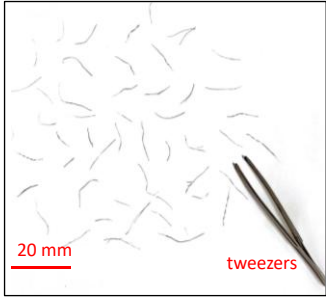
2.4 Hydro-physical response of air-dried and pre-soaked fibres

In classical soil mechanics, the (gravimetric) water content is a key and simple measure of a hydraulic gravimetric variable that controls soil engineering behaviour. Direct measurements, involving water and solid masses, are commonly taken in the laboratory following the standards (e.g., [43]).

When additives are used to improve soil behaviour, their effect generally depends on the water content of the mixtures in the after-curing configuration. This is why we have focused on measuring the water content

of the fibres under AD or PS conditions at different heating temperatures. The water content measurements were determined following the ASTM D02216-98 [44] standard for soil water content determinations (*i.e.*, 105°C for 24 hours) and a non-standard method by keeping the fibres at 50°C for 24 hours to prevent any loss of lignin or biomass. For both AD and PS fibres, measurements were taken both in a bundled (B) configuration and after careful separation (S) with tweezers. The results reported in *Table 2* show that for separated PS (PS_S) and bundled PS (PS_B), higher heating temperatures result in 7.0% and 10.4% increases in water content, respectively, relative to the lower heating temperature, attributed to the loss of some water and biological components. This result is consistent with the literature on the burning temperatures of lignin and cellulose in *P. oceanica* fibres, as reported in thermogravimetric analyses over similar temperature intervals [45]. Moreover, increases of 18.3% and 21.7% in water content are recorded for PS fibres in the bundled configuration compared with the separate ones at 50°C and 105°C, respectively. This suggests that the additional water retained in the bundled fibres is due to the capillary water content between fibres. This variation can significantly impact the system's hydraulic response, particularly the water retention curve, which will be explored in Section 4.5.

*Table 2: Effect of different temperatures on the water content of *P. oceanica* fibres.*

24h-oven temperature (°C)	Bundled (B) configuration		Separated (S) configuration	
				
	W_{AD_B} (%)	W_{PS_B} (%)	W_{AD_S} (%)	W_{PS_S} (%)
105	18.10	153.7	17.53	132.0
50	13.70	143.3	13.25	125.0

The solid density of *P. oceanica* fibres was determined using wet and dry pycnometer methods, see Sections 3.1 and 3.2, which provided average values of 1.33 Mg/m³ and 1.31 Mg/m³, respectively, showing consistency between the two methods. In this study, the wet pycnometer value $\rho_s = 1.33$ Mg/m³ was used for all calculations [46]. This measurement is essential for calculating fibre void ratio e , which is the ratio of the

volume of voids (V_v) to the volume of solid (V_s), and the porosity (*i.e.*, $n=V_v/V_t$, already defined in Section 2.2.2), based on relations commonly used for porous materials (see *Table 3* and refer to supplementary material).

Porosity was quantified for both hydraulic states (AD and PS) using two image-based approaches (Sections 2.2.2 and 3.4). The 2D ImageJ analyses (from binarised cross-sections) indicated a porosity of 0.248 ± 0.013 for AD fibres and 0.271 ± 0.022 for PS fibres. The 3D Syn-nCT analyses (Section 2.2.2 and *Table 3*) confirmed the same trend, with consistently higher porosity in PS fibres, due to water absorption and swelling that enlarge the lumen and longitudinal channels.

As an independent check, porosity was also computed from classical porous-media relations using bulk density ρ measured in both states (refer to supplementary materials and *Table 3*), the corresponding water content w , and the fibre solid density $\rho_s = 1.33 \text{ Mg/m}^3$. Approximately 50 fibres were scanned, and image processing in ImageJ was used to determine their total length. The mass of the fibres was also measured, enabling the calculation of the average mass of a single fibre. Using the average fibre volume from X-ray tomography employed to characterise fibres prior to tensile tests, the average bulk saturated density of individual fibres was determined for both PS and AD fibres (Section 3.6).

Table 3 presents the results of the calculations alongside measurements of individual PS and AD fibres conducted at the Syn-nCT. Interestingly, the calculated values closely match the experimental measurements. While porosity is slightly overestimated due to the empirical relations used for porous materials, this difference is minor and emphasises the practical utility of such relations. They provide a reliable method for initial engineering estimates, particularly given limited access to detailed 3D measurement techniques. Consequently, the small differences between the Syn-nCT porosity and the porosity derived from classical porous-media relations probably stem from the μ CT definition (lumen/open channels only), which excludes superficial surface porosity (*Figure 1e*).

Table 3: Comparison between the measurements carried out on Syn-nCT and the calculations from the analytical relations used for porous materials.

	Syn-nCT measurements		Calculated values for the porous materials	
PS fibre	$V_t \text{ (cm}^3\text{)}$	2.86×10^{-6}	Mass of single fibres (g)	6.82×10^{-5}
	$V_s \text{ (cm}^3\text{)}$	2.24×10^{-6}	Average volume of fibres (cm ³)	3.60×10^{-5}

	$V_v (cm^3)$	6.20×10^{-7}	Bulk density $\rho (Mg/m^3)$	1.89
	e	0.277	$e = \rho_s(1+w)/\rho-1$	0.583
	-	-	Water content w (%)	125
	n	0.217	$n = e/(1+e)$	0.368
AD fibre	$V_t (cm^3)$	3.07×10^{-6}	Mass of single fibres (g)	5.93×10^{-5}
	$V_s (cm^3)$	2.48×10^{-6}	Average Volume of fibres (cm^3)	6.12×10^{-5}
	$V_v (cm^3)$	5.96×10^{-7}	Bulk density $\rho (Mg/m^3)$	0.969
	e	0.240	$e = \rho_s(1+w)/\rho-1$	0.561
	-	-	Water content w (%)	13.7
	n	0.194	$n = e/(1+e)$	0.359

The water retention properties during fibre-atmosphere interactions are described by the Water Retention Curve (WRC), which relates the water content of the porous fibre to the corresponding energy state of the pore water. In this context, total suction ψ is used as a measure of the energy per unit volume required to move water from the reference state (pure free water) into the porous fibre. Water within the fibre is in equilibrium with its vapour according to the psychrometric law, enabling the determination of total suction from the relative humidity of the air (RH), which is easier to measure (Section 3.7) [47].

Figure 8 illustrates the WRC of class 2 (Figure 3) *P. oceanica* fibres during drying at $RH = 50\%$ and subsequent wetting at $RH = 98\%$, which is essential for understanding fibre–sediment interactions (i.e. water content exchanges and total suction equalisation processes) and optimising fibre preparation and mixing procedures at various water contents of the fibres. The water content w was normalised by the maximum value at saturation contained in pores, w_{sat} , to represent the degree of saturation S_r (the proportion of the volume of the voids occupied by water), assuming a constant void volume.

To investigate these drying and wetting curves, total suction and water content were measured under equilibrium conditions, which are defined here as the states in which the *P. oceanica* fibres are maintained in a controlled-RH chamber without any further change in water mass. Along the drying path, fibres were first saturated in seawater (33.17 g/L NaCl) and the excess surface water was gently removed as indicated in section 2.2. Afterwards, fibres were exposed to 50% relative humidity to monitor water content loss over time across different equilibrium stages. In the wetting path, dry fibres were placed in humid chambers (98% RH with 33.17 g/L NaCl) to assess water uptake via vapour transfer, thereby preventing excess surface water and emphasising storage primarily due to capillarity within the inter-fibre pore space.

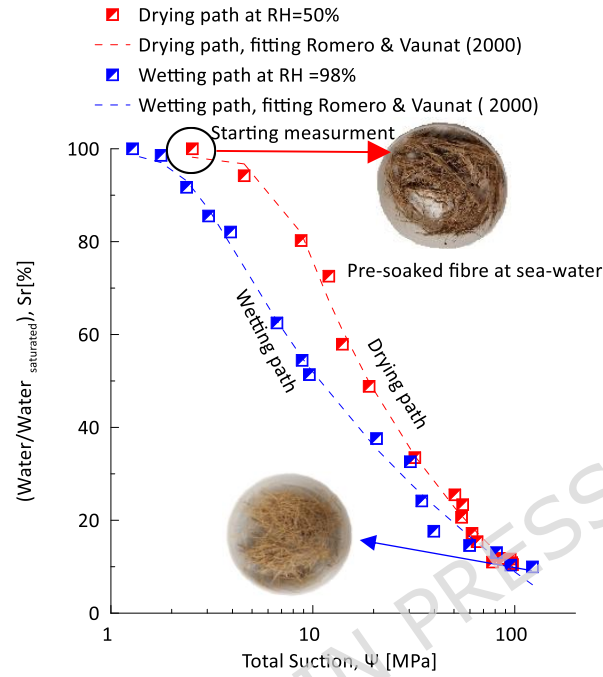
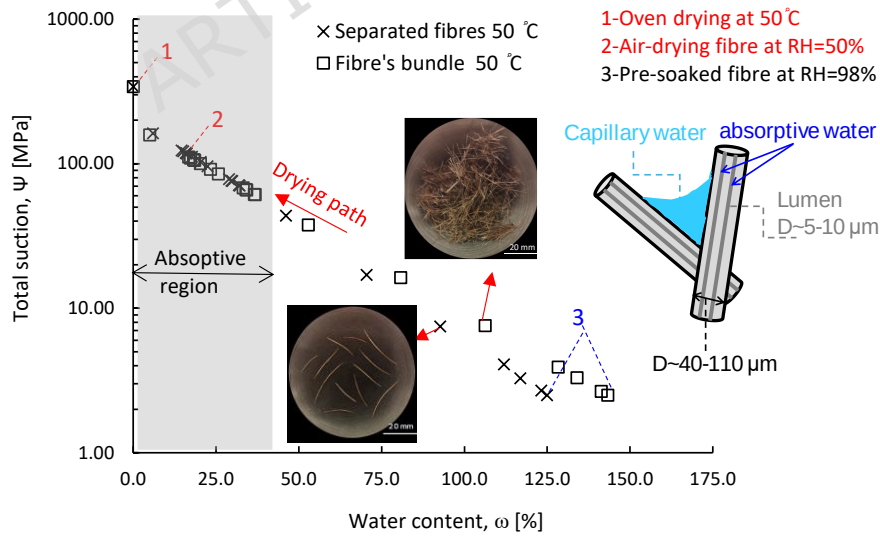
The resulting WRCs exhibit clear hysteresis, reflecting changes in pore structure and connectivity, and in pore volume during fibre shrinkage and expansion, as well as different mechanisms of water storage. Two main contributions are identified: the absorption of water within the intra-fibre porosity in lumens, and the capillary menisci between fibres in the bundled configuration. Results indicate that capillarity is dominant in bundles at high water contents with lower total suction. *Figure 8* also shows the fitting of the experimental data using the Romero and Vaunat expression [48], a modified version of the van Genuchten model [49], normally used for fine-grained soils. The good fit of the data suggests that this model can be extended to this kind of lignocellulosic natural fibres, although it assumes a constant void ratio throughout the processes.

To further clarify the hysteresis response and better distinguish the contributions of the two storage mechanisms in the porous network, fibres were tested in both bundled and separated states during drying after being saturated in seawater and the excess surface water removed. As shown in *Figure 9*, there is no difference between the two scenarios in the grey-highlighted absorption domain at water contents below 40%. When the fibres are oven-dried at around 50°C (point 1 in *Figure 9*) —exposed to very low humidity (~10%, recorded by RH sensors) or subjected to high total suction (~342 MPa, estimated using the psychrometric expression)—most of the absorbed water is removed. At water contents higher than 40%, clear differences between the two scenarios emerge: the bundle configuration retains more water than the separated one for a given total suction. This additional water content is retained within the inter-fibre space, as this low-suction range of the curve is controlled mainly by capillary effects. Based on these observations, the authors hypothesise a model involving two distinct water-retention scenarios for natural fibres like *P. oceanica*. In the separated-fibre scenario, water retention is governed primarily by intra-fibre absorption, where water is stored within the fibre lumen (pores approximately 5–10 µm in diameter). In contrast, in the fibre-bundle scenario, water is retained not only within the lumen's intra-pores but also in the inter-fibre spaces, where capillary forces hold additional water. This results in a higher overall water-retention capacity of fibre bundles at low total suctions due to capillary storage between fibres.

The fitted parameters for the hysteretic drying and wetting paths are summarised in *Table 4*. As shown in the table, the air-entry parameter during drying (9.46 MPa) is much higher than during wetting (3.24 MPa). Here the parameter $a = 1000$ MPa defines the maximum total suction at which the degree of saturation, S_r , tends to zero.

Table 4. Fitted parameters for drying and wetting paths for the *P. oceanica* fibre

Mixtures	$1/\alpha$ (MPa)	n	m	a (MPa)
Drying path	9.46	2.51	0.34	1000
Wetting path	3.24	2.70	0.21	1000

Figure 8: Water retention curves during drying and wetting paths for *P. oceanica* fibre.Figure 9: Water retention capacity of *P. oceanica* fibres in both the bundled and separated scenarios, during a drying path with a schematic representation of the intra-fibre absorption domain and the inter-fibre region with dominant capillary water.

2.5 Engineering application and treatment limitations

2.5.1 Fibre-reinforced cement-treatments of natural dredged sediment

The unconfined compression tests were performed to evaluate the effect of *P. oceanica* fibres on the mechanical behaviour of cement-treated sediment at the mixture scale. The sediment used in this study was taken from the filling basin of the port of Taranto in southern Italy and was mixed to cement or cement and fibres from its natural condition ($w_0 = 71.04\%$). The cement used is a blast furnace slag cement. See the following material section for further information.

Figure 10 shows the unconfined compression test (UCT) results after 7 and 28 days of curing. The fibre-reinforced mixtures, DS16T1FAD and DS16T1FPS, showed UCS values similar to, or slightly lower than, the control mixture DS16T. From 7 to 28 days, UCS increased by 88.3% for DS16T, 97.4% for DS16T1FAD, and 76.7% for DS16T1FPS. This indicates that peak strength was mainly governed by cementation of the sediment–binder matrix.

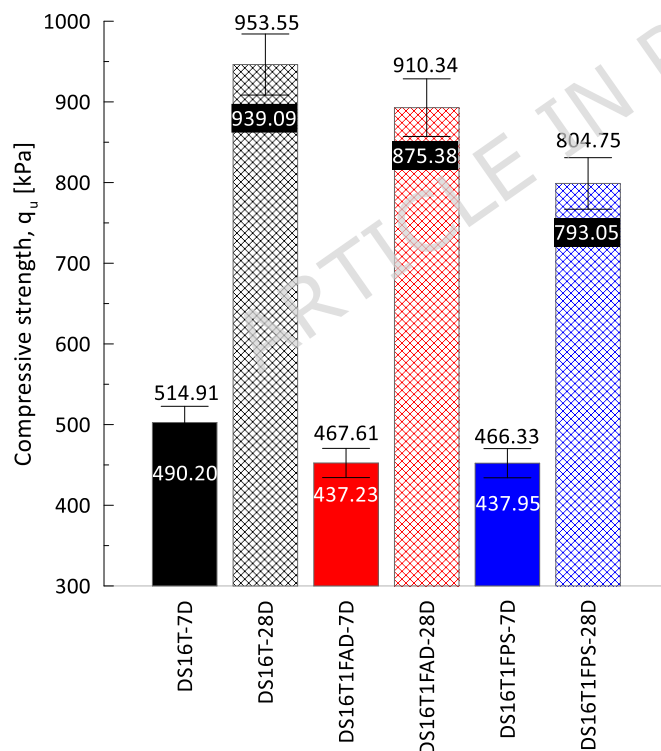


Figure 10. Compressive strength of stabilized and fibre-reinforced sediment after 7 and 28 days of curing.

The stress–strain curves in

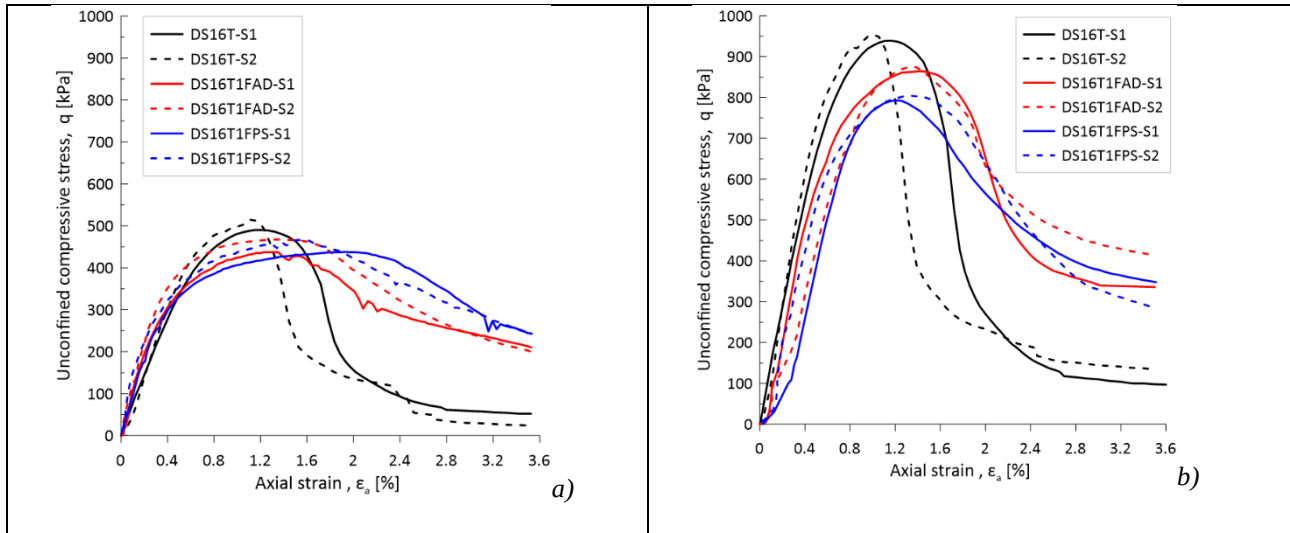


Figure 11a and b show a clear difference in post-peak behaviour. The control mixture DS16T showed

a brittle response, with a sudden stress drop after the peak [50]. In contrast, the fibre-reinforced mixtures showed a more gradual post-peak softening and maintained higher residual stress at larger axial strains. This means that the fibres were mainly activated after cracking. They bridged cracks, limited crack opening, delayed crack propagation, and improved stress redistribution. This fibre-bridging mechanism and the associated improvement in post-peak ductility have been commonly reported for fibre-reinforced cemented soils and related fibre-reinforced cementitious composites [50-53].

The failure strain also confirms this ductile response. The control mixture reached failure strains of about 1.20% after 7 days and 1.16% after 28 days, while the fibre-reinforced mixtures reached peak strength at higher axial strains. These values are within the typical range of 1–4% reported for fibre-reinforced cemented soils [54, 55]. Therefore, the main effect of adding 1% *P. oceanica* fibres was not to increase peak UCS, but to improve ductility, residual resistance, and post-peak deformation capacity. This agrees with the fibre-scale results, where AD fibres showed higher tensile resistance, while PS fibres showed higher tortuosity, toughness, and deformation capacity.

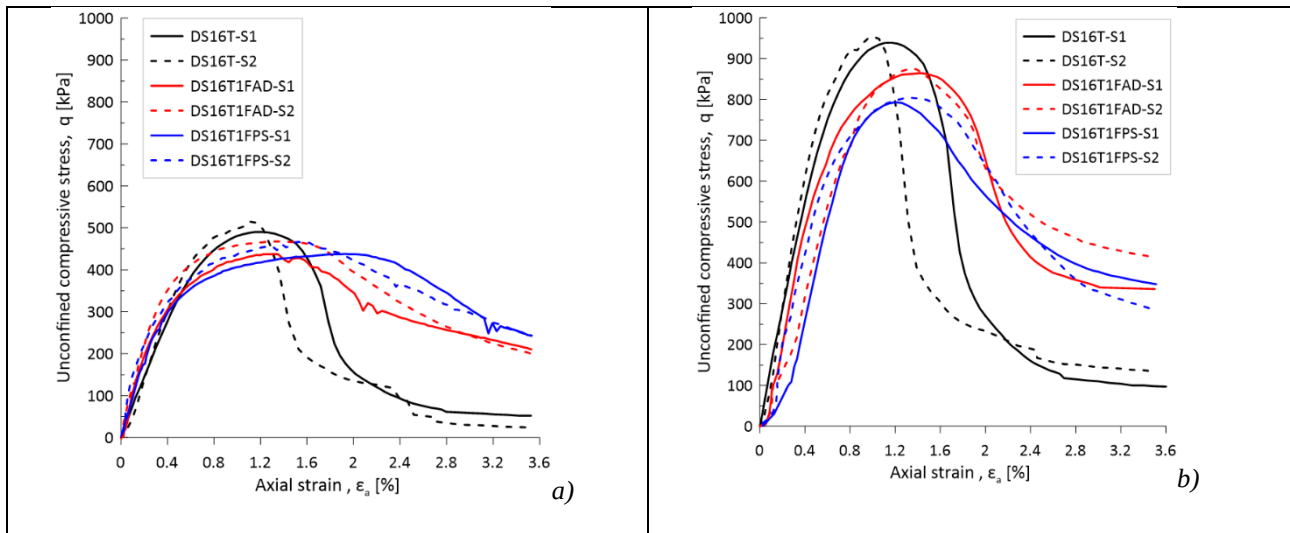
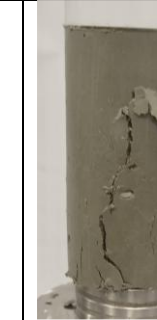
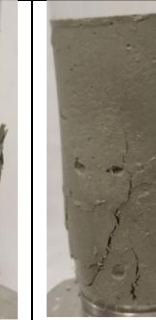


Figure 11: UCT results for dredged sediment treated with cement and different pretreatment of *Posidonia* fibres air-dry FAD, pre-soaked fibres FPS), after, a) 7 days, b) 28 days curing time.

The crack patterns in Table 5 further support this interpretation. The control mixture showed a brittle failure mode, with a limited number of wide cracks and one dominant macrocrack. This indicates localized cracking and sudden splitting after peak stress, which is commonly observed in cement-treated soils without fibres [51]. In contrast, the fibre-reinforced mixtures showed several finer cracks with smaller widths, often following inclined or zigzag paths. This shows that the fibres reduced strain localization and promoted a more distributed failure mechanism. The selected fibre length, surface morphology, natural tortuosity, and tensile resistance helped the fibres interact with the cemented matrix, bridge cracks, and delay crack propagation.

Table 5. post-test crack patterns for all mixtures after 7, 28 days curing time

Samples	DS16T-S1	DS16T-S2	DS16T1FAD-S1	DS16T1FAD-S2	DS16T1FPS-S1	DS16T1FPS-S2
7D-curing						



The UPV results in Figure 12 also support the UCS interpretation. For all mixtures, UPV increased from 7 to 28 days, indicating progressive matrix densification and cement bond development. At the same curing time, the fibre-reinforced mixtures showed UPV values close to those of the control mixture, suggesting that fibre inclusion did not produce a significant increase in global voids or loss of overall compactness. However, UPV mainly reflects the global stiffness, porosity, and cementation state of the specimen, and does not directly assess fibre–matrix adhesion. Therefore, although possible local interface effects cannot be completely excluded, the UPV results do not indicate a substantial deterioration of the internal structure.

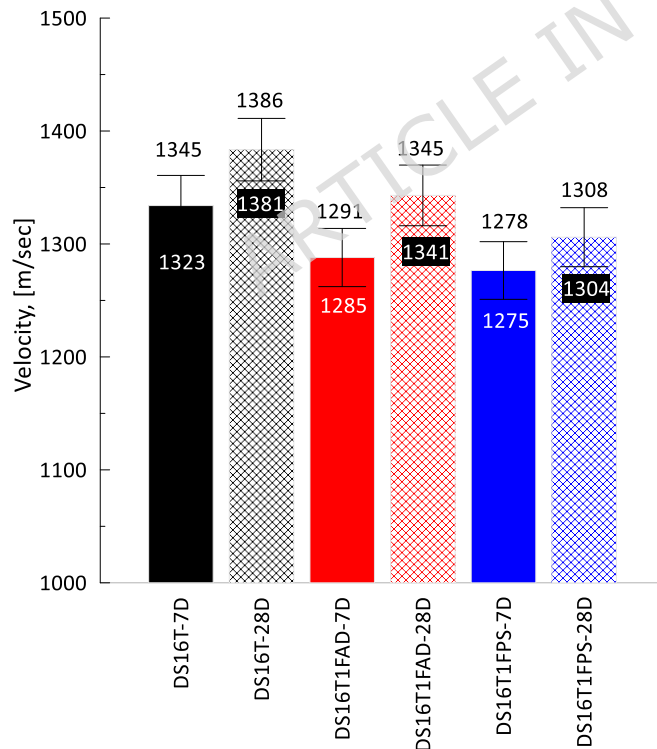


Figure 12: Ultrasonic pulse velocity test results of fibre-reinforced and unreinforced sediment-cement mixtures.

2.5.2 Treatment limitations

The results show that *P. oceanica* fibres can be used as sustainable bio-based reinforcement for cement-treated sediments, especially when the main objective is to reduce brittleness and improve post-peak behaviour, crack distribution, ductility, rather than increasing peak strength.

However, these results were obtained under short-term laboratory conditions, using one sediment type, one binder content, and one fibre dosage. Therefore, they should not be directly extended to all soils or field conditions. Further tests are needed for clayey, silty, sandy, organic, saline, and highly alkaline soils, because soil mineralogy, pore-water chemistry, pH, and microbial activity may affect fibre–matrix bonding and durability.

Durability is also an important limitation. Natural fibres in cementitious materials may degrade because of alkaline hydrolysis, lumen and cell-wall mineralization, and loss of bonding during wetting–drying cycles [56]. These mechanisms are relevant for *P. oceanica* fibres exposed to long-term curing, seawater, and alkaline pore water.

Fibre treatment may improve long-term performance. Stefanidou et al. [19] showed that hydrothermal and alkaline treatments of *P. oceanica* fibres can reduce hygroscopicity, improve durability, and enhance fibre–matrix adherence.

Finally, practical application requires control of fibre length, dosage, moisture condition, mixing sequence, and compaction. The image-based fibre selection method proposed here provides a useful first step to reduce clustering and improve fibre dispersion. Overall, this study provides a laboratory-scale basis for using *P. oceanica* fibres, while further durability, compatibility, and field-scale studies are required before design recommendations can be defined.

3 Conclusion

This study presents the first comprehensive analysis of beached *P. oceanica* fibres for soil reinforcement, integrating microstructural, chemical, hydraulic, and mechanical investigations across scales—from the nanoscale to the bulk material.

A novel image-based method was developed to predict fibre length from ball diameter, providing a practical tool for selecting fibre length classes. This is particularly helpful when adding fibres for material reinforcement, as selecting fibre length can reduce clustering and improve the internal space grid, thereby optimising fibre efficiency.

Comparisons between void ratio and porosity calculations based on empirical relations used for porous materials and measurements from Syn-nCT showed a small discrepancy and, in fact, highlighted the practical usefulness of such relations for preliminary engineering estimates, especially given the limited access to detailed 3D measurement techniques.

Using FE-SEM and Syn-nCT, we found that AD fibres exhibit lower porosity and tortuosity but higher tensile strength, whereas PS fibres display greater porosity and tortuosity along with enhanced toughness due to geometric alignment and water-induced plastic-stretching effects. These behaviours stem from the fibres' unique morphology, dominated by hollow lumens that serve as interconnected water pathways enclosed by intrinsically hygroscopic lignocellulosic walls. Moreover, the EDX elemental analysis provided evidence that carbon and oxygen, primary constituents of biopolymers such as cellulose and lignin, are homogeneously distributed throughout the fibre structure, thus predisposing to more uniform hydraulic properties and mechanical performance.

Water retention tests revealed two distinct domains: absorbed water stored within the intra-pores of lumens, and capillary water held between fibres in bundles, with bundles retaining roughly 18% more water than separated fibres on saturation. These results shed light on fibre-atmosphere interactions and are fundamental to optimising fibre preparation and mixing procedures based on the various water contents of the fibres.

Together, these findings highlight the untapped potential of beached *P. oceanica* fibres for simultaneously enhancing mechanical strength and water retention in soils, offering a sustainable alternative to synthetic fibres and a new, practical pathway for valorising this abundant, often landfilled, biological waste. This perspective aligns with broader efforts to develop bioinspired and renewable fibrous materials for engineering applications, as well as recent demonstrations that naturally occurring plant-based fibrous architectures can be effectively exploited for sustainable material reinforcement [1, 10, 57].

Engineering applications performed by comparing the strength response of sediment-cement mixtures with and without fibres have confirmed that *P. oceanica* fibre addition did not significantly change the peak strength but clearly improved the post-peak response, producing more gradual softening, higher residual resistance at larger strains, distributed cracking, improved ductility.

Future studies should explore long-term durability, biodegradation, alkaline degradation, fibre–matrix bonding, compatibility with different soil types and pore-water chemistries.

4 Materials and Methods

4.1 Materials

Posidonia oceanica fibres

Beached *P. oceanica* fibre balls, known as Aegagropiles, were used in this study [11]. These spherical aggregates are naturally formed by the rolling and compaction of detached seagrass fibres under seawater movement. The collected fibres were first air-dried under laboratory conditions (relative humidity of 50%). Fibre balls with different diameters were analysed to establish the relationship between ball diameter and fibre length [33]. Based on this analysis, fibres belonging mainly to the 10–25 mm length class were selected for the following tests, because this range reduces clustering while allowing the formation of a reinforcing network in cement-treated sediment [34].

Dredged sediment

The dredged sediment (DS) used in this study was obtained from the filling basin of the Port of Taranto in southern Italy. In its natural condition, the sediment was in a slurry state, with a negative consistency index ($CI = -0.41$) and a high natural water content ($w_o = 71.08\%$, corresponding to $w_o = 1.22 W_L$). The particle size distribution showed that the material was mainly composed of silt (63.8%), followed by clay (30.4%) and sand (5.8%). The specific gravity of the soil particles was $G_s = 2.67$. Based on the Atterberg limits measured on the whole material, the sediment was classified as a high-plasticity clay (CH) according to the USCS classification system (ASTM D422) [58]

Blast furnace slag cement

The hydraulic binder utilized in this study is a commercial blast furnace slag cement (32.5N, UNI EN 197-1). This cement contains 36–65% granulated blast furnace slag, a recycled by-product from iron ore processing. Identified as type T, it is suitable for moderately aggressive conditions, including exposure to chlorides,

moderate sulphate environments, leaching waters, and contact with glycerides. Compared to ordinary Portland cement (OPC), it features lower calcium oxide (CaO) content but higher levels of aluminium oxide (Al₂O₃), silicon dioxide (SiO₂), and magnesium oxide (MgO), along with a higher specific surface area (BET: 1.4 m²/g). XRD analysis indicated significant amounts of alite, belite, tetracalcium aluminoferrite (C₄AF), bassanite (calcium sulfate hemihydrate), and calcite. The associated CO₂ emissions are under 550 kg/t, significantly lower than conventional Portland cement (approximately 750 kg/t).

4.2 Fibre physical characterisation

Wet pycnometer

The specific gravity (Gs) of the *P. oceanica* fibre was determined following ASTM D854-14 [59], adapted for organic fibres in powdered form. The fibres were first oven-dried at 50 °C for 24 hours. The dried material was then ground into powder and passed through a No. 200 sieve (75 µm) to achieve uniform particle size. For the wet pycnometer method, a known mass of the powdered fibre was placed into a clean, dry pycnometer. Distilled water was added until the level was slightly above the fibre powder, and the pycnometer was left undisturbed for 12 hours to allow full water absorption by the sample. After this period, suction was applied at a pressure of 100 mm Hg for at least 30 minutes while the pycnometer was gently shaken inside a desiccator to remove entrapped air bubbles. The pycnometer was then carefully filled with distilled water to the calibration mark, the outer surface dried, and the mass recorded. The temperature of the water was also measured and noted for correction. Three replicate measurements were carried out, yielding an average γ_s value of 1.33 Table 6.

Table 6: Specific gravity and solid unit weight of *P. oceanica* fibres determined by the water pycnometer method

Samples name	Mass of <i>P. oceanica</i> fibres powder (g)	Specific Gravity (Gs)	Solid unit weight γ_s (g/cm ³) Water unit weight γ_w (0.99621 (g/cm ³) in 20 °C)
Sample 1	12	1.3362	1.3312
Sample 2	12	1.3523	1.3472
Sample 3	12	1.3426	1.3376

Dry pycnometer

In addition to the water pycnometer tests, the same powdered *P. oceanica* fibre samples (prepared as described for the wet pycnometer method) were also analysed using helium pycnometer based on [60]. The fibre volume for each sample was measured 10 times, with standard deviations calculated, ultimately providing the final average fibre volume. This process was repeated for three identical fibre samples to obtain an average solid density. The weight of the sample was measured with a precision balance capable of measuring up to 0.0001 g, allowing for accurate calculation of the solid density of the fibres.

$$\Delta P \times \Delta V = nRT \quad \text{Equation 1}$$

where P is the pressure (kPa), V is the volume of the gas displaced, n is the number of moles of helium gas, R is the universal gas constant, and T is the absolute temperature in Kelvin.

The dry pycnometer results are presented in Table 7, with an average value of 1.31. Three replicate measurements gave an average value of 1.31 (g/cm³), which showed consistency across two methods. For subsequent analyses and calculations, the wet pycnometer value (1.33) was adopted.

Table 7: Solid unit weight (γ_s) of samples determined by the pycnometer method.

Samples name	Solid volume Vs (cm ³)	Solid mass Ms (g)	Solid unit weight γ_s (g/cm ³)	Standard deviation (Std) (cm ³)
Sample 1	0.4695	0.6164	1.312	0.0003
Sample 2	0.451	0.5777	1.281	0.0009
Sample 3	0.6588	0.8854	1.344	0.0005

Bulk density of dry and wet fibres

The bulk density of the fibres was measured in two hydraulic states: air-dried (w=13.7%) and saturated (w=125%). For each state, fifty fibres were pre-soaked in water for 48 hours to achieve full saturation. After soaking, the superficial water was gently removed using tissue paper. The fibres were then scanned, and image processing was performed using ImageJ, applying a threshold of 250/255 to determine the total length of all fibres (L_{50}) (Figure 13a). The weight of the total fibres was also recorded (M_{50}), allowing for the calculation of the average weight of a single fibre. Two of these 50 fibres were selected for tensile testing. Before the tensile test, these two fibres were scanned using CT tomography to determine their average volumes (Figure 15b). The average volume of these three fibres was used as a representative value for a single fibre. Using the average length obtained from scanning the 50 fibres and the average fibre volume from CT tomography, the

bulk saturated density of a single fibre was determined. The same process was repeated for air-dry fibres to determine their bulk dry density (Figure 13b).

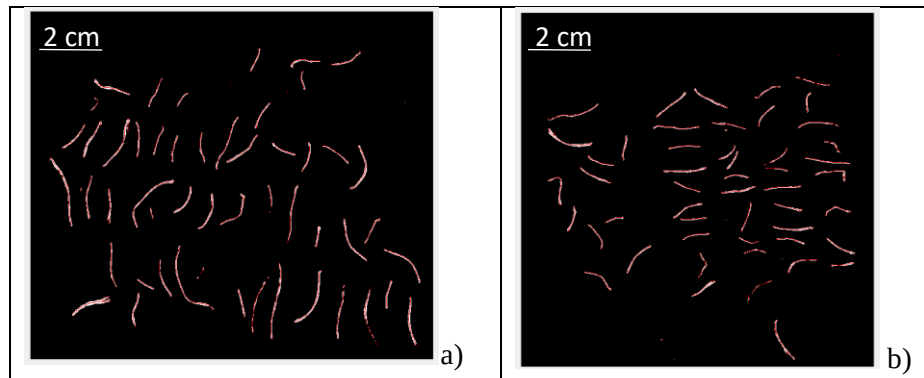


Figure 13: ImageJ analysis, scanned of 50 fibres a) pre-soaked fibres, b) air dried fibres

4.3 Microstructural and chemical characterisation

FE-SEM analysis

Based on the elemental analysis EDAX of *P. oceanica* fibres, the atomic ratio of oxygen to carbon (O/C) was calculated using their respective mass percentages and atomic weights—16 g/mol for oxygen and 12.01 g/mol for carbon [61]. The atomic ratio was determined as:

$$\text{Atomic ratio O/C} = \frac{\left(\frac{\text{Mass \% of O}}{\text{atomic weight of O}} \right)}{\left(\frac{\text{Mass \% of C}}{\text{atomic weight of C}} \right)} \quad \text{Equation 2}$$

X-ray tomography at synchrotron

Nano-tomography was carried out at the ID16B beamline of the European Synchrotron Radiation Facility (ESRF) optimized for high-resolution nanoscale imaging at 29.6 keV. A Kirkpatrick-Baez (KB) mirror system focused the X-ray beam to $50 \times 50 \text{ nm}^2$, generating a collimated conical beam for high spatial resolution imaging. Phase contrast tomography was employed to enhance edge contrast and reveal fine-scale structures, providing superior resolution compared to conventional X-ray absorption tomography [62]. Imaging was performed with a $64 \times 54 \text{ }\mu\text{m}^2$ Field of View (FoV) and a voxel size of 250 nm. The samples underwent a 360° rotation, capturing 2,500 projections per scan, with an exposure time of 0.07 s per projection.

Data processing followed a two-step approach: first, phase retrieval was performed using PyNX [63], applying a Paganin-like method ($\delta/\beta=180$) to enhance contrast between different material densities, improving the visibility of internal structures. Next, 3D volume reconstruction was carried out using Nabu, an ESRF-developed tomography processing software [64] which uses the filtered back-projection (FBP) algorithm.

The 2D method to calculate porosity was that of by analysing 2048 sequential cross-sections by applying manual threshold (of 155/255) in the 8-bit images, to isolate fibre's solids from pores in Image J software. Once binarized images were obtained, pixels belonging to either pores (V_v) or solids (V_s) were automatically evaluated, to give estimations of porosity for each cross-section and averaging the results. In contrast, the 3D analysis, conducted with Dragonfly software [65], which was done after manual thresholding (of 43858/65535) of base images, to segment the open channel as a pores (V_v) and solids as (V_s) provided a direct measurement of actual pore volumes, capturing the complexity of the fibre's internal structure more accurately. All these segmentations and thresholds and statistical analysis can be found in the supplementary files (refer to supplementary materials).

Figure 14a, b shows horizontal slices of air-dried and pre-soaked *P. oceanica* fibre that were obtained from reconstruction of synchrotron X-ray Tomography. After applying manual thresholding, the distinction between fibre pores and solid regions can be observed in Figure 14c for the air-dried fibre and in Figure 14d for the pre-soaked fibres (refer to Figure S1).

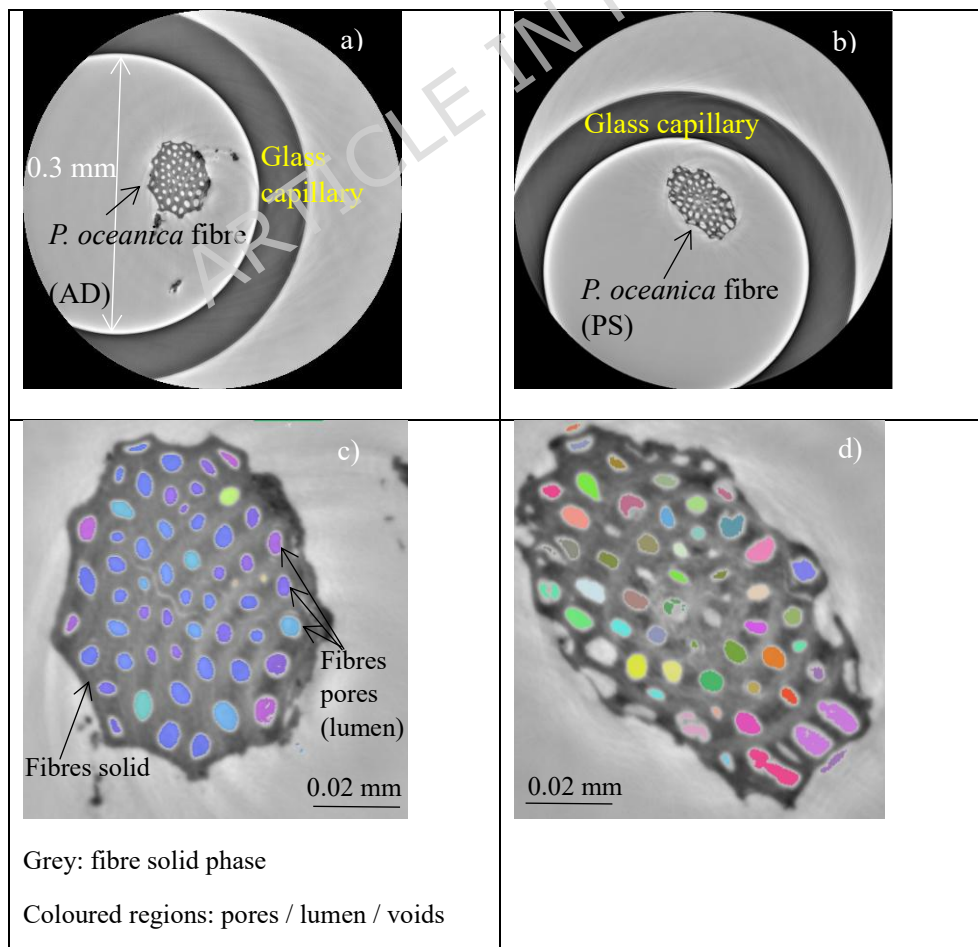


Figure 14: Syn-nCT a) reconstructed images of air-dried fibre, b) reconstructed images of pre-soaked fibre, c) segmentation of pores and fibres solid for air-dried fibre; and d) segmentation of pores and fibres solid for pre-soaked fibre.

4.4 Fibre tensile testing and image-based geometry

The fibres, including both air-dried (AD) and pre-soaked (PS) samples, were first prepared in a glass container for measuring their mean diameters using X-Ray tomography with a resolution of $3\mu\text{m}$ (Figure 15a). The reconstructed images were then processed by applying a threshold of 80/255 to isolate the fibres from the glass container (Figure 15b (also refer to Figure S2)) using Dragonfly software for pre-soaked and air-dried fibres, respectively (refer to supplementary materials). The fibre volume was measured after segmenting the fibres from 3D imaging data (micro-CT scans) and calculating the voxel-based volume. The total fibre volume was obtained by summing the voxel counts within the segmented region and converting it using the voxel size (Vt). The corresponding diameters (D) were then derived using the $D = \sqrt{\frac{4Vt}{\pi L}}$. The actual fibre length (L) was measured using Dragonfly software by extracting the 3D centreline of segmented fibres and calculating the actual curvilinear path.

Also, tortuosity was determined as the ratio of the measured actual fibre length to the straight-line distance between its endpoints. Tortuosity was measured using MATLAB, following a structured approach. Initially, each 2D cross-section was binarized and segmented in a similar method to volume threshold measurement in ImageJ software. After segmentation (Figure 16a), some fibres showed small branches in their geometry (black pixels in Figure 16b). The skeleton path (main branch with the longest path length) in 3D was identified with centroids of the fibres (red pixels in (Figure 16b, c), and the small branches were pruned (Figure 16c) (refer to Figure S3, S4, S5, and S6). Therefore, the longest connected red path was used to represent the main length. In the case of fibres without any bifurcations, the naturally curved or “snake-like” shape was directly selected as the main path in 3D. For all fibres, tortuosity was calculated as the ratio of the actual fibre length (main path) to the straight-line distance between its endpoints (refer to supplementary materials).

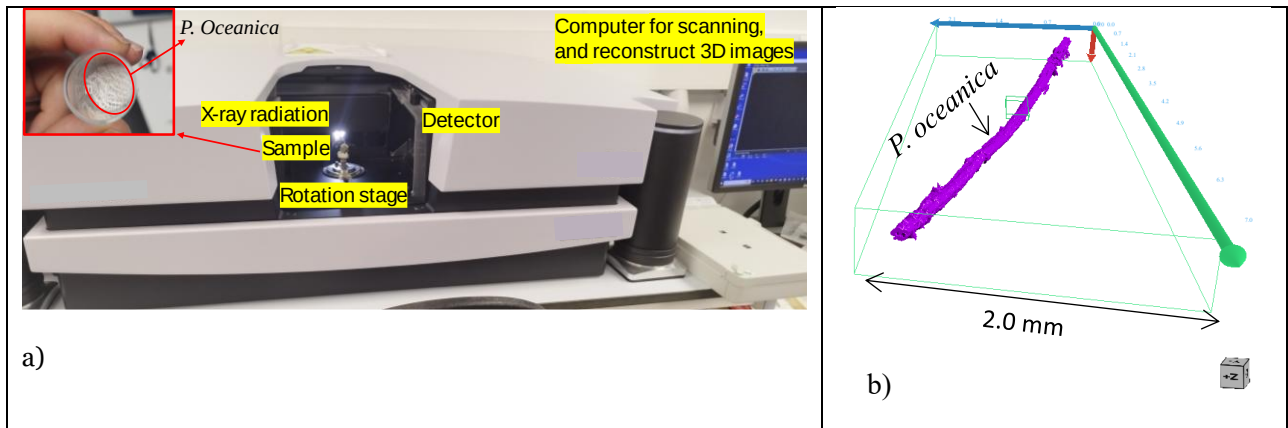


Figure 15: a) X-Ray Tomography imaging for *P. oceanica* fibres; and b) X-Ray tomography images of *P. oceanica* fibres after applying threshold.

The tensile testing of dry and pre-soaked *P. oceanica* fibres was carried out according to ASTM C1557–03 [38]. The TA HR30 Discovery Hybrid Rheometer equipped with top and bottom clamps along with a 50 N capacity load cell was used. The equipment allows testing of fibres up to a maximum length of 20 mm. After CT tomography images, the sample was fixed in a paper frame with glue [39], and subsequently fixed in a clamp of the tensile testing equipment. A constant displacement rate of 1 mm/min was applied during the tests, which were conducted in a controlled laboratory environment with a relative humidity of 50% and a temperature of 22°C. Results from tests in which fibre failure occurred in the vicinity or by pull-out from the clamps were discarded. For each hydraulic path, three samples were prepared and tested. One sample in air-dried and pre-soaked hydraulic paths was rejected due to slippage and failure near the clamp.

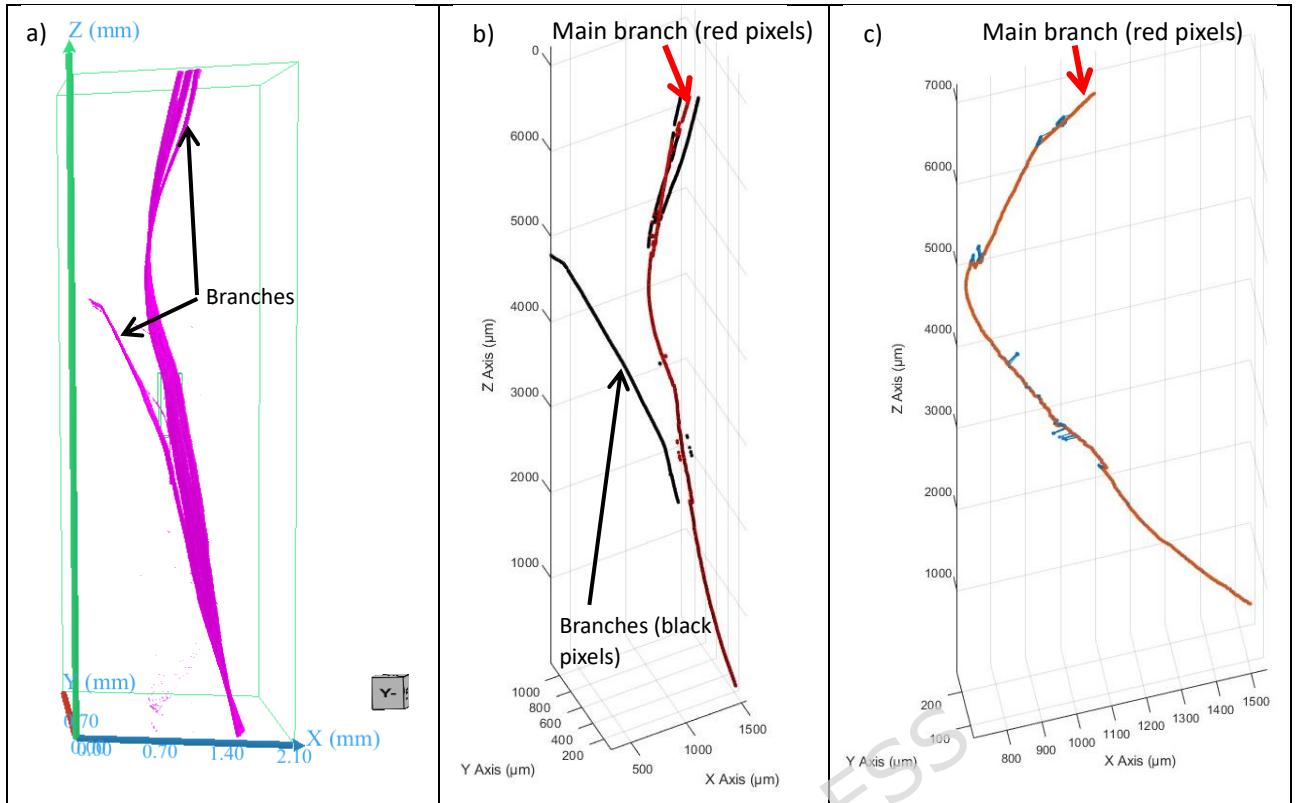


Figure 16: a) Segmented fibres (PS-S2), MATLAB Analysis of the Main Branch in pre-soaked fibres (PS-S2) (b) Original fibre images displaying bifurcation; and (c) Main branch after pruning the bifurcations and noises considering the curvature length of fibres (PS-S2).

The axial strain, was determined as:

$$\varepsilon = \frac{\Delta l}{l_0} \quad \text{Equation 3}$$

Δl is the variation in length and l_0 is the initial length. The initial length was evaluated as the straight-line distance.

For calculating the tensile strength, the modified areas were determined as:

$$A_0 = \frac{\pi D^2}{4}, A = \frac{A_0}{1 - \varepsilon_T}, \varepsilon_T = -\nu \times \varepsilon_L \quad \text{Equation 4}$$

The initial cross-sectional area of the fibres (A_0) was calculated using the average fibre diameter (D). The modified cross-sectional area (A) can be determined based on the transversal strain (ε_T) and the initial average area (A_0) of the fibres. The transverse strain is calculated from the measured longitudinal strain (ε_L), considering an average Poisson's ratio of 0.2-0.4 for lignin and cellulose natural fibres [66, 67]. In this study, Poisson's ratio of 0.4 was selected to modify the area for calculating the tensile strength. This upper-bound value was adopted because Poisson's ratio was not measured directly in this study, allowing a conservative

correction of the fibre cross-sectional area. Varying ν from 0.2 to 0.4 changed the corrected tensile stress by only about 5% within the measured strain range and did not alter the observed trend between air-dried and pre-soaked fibres. Toughness is determined by integrating the stress-strain curve, representing the mechanical deformation energy per unit volume before fracture. Mathematically, it is expressed as:

$$\text{Toughness (KJ/m}^3\text{)} = \int_0^{\varepsilon_f} \sigma_t d\varepsilon \quad \text{Equation 5}$$

where the ε is strain, ε_f is the strain upon failure, and σ_t is the tensile stress.

4.5 Moisture conditioning and water-retention testing

Total suction was measured using the dew point method with the WP4C apparatus (Decagon Devices, Pullman, WA, USA), following ASTM D6836-02(2008) e2 standards and applying the psychrometric law [68]. The WP4C (*Figure 17a*), with a measurement range of 0 to 300 MPa, provides an accuracy of ± 0.05 MPa for values between 0 and 5 MPa and 1% full-scale accuracy for measurements from 5 MPa to 300 MPa. Total suction (Ψ_{total}) in MPa, was calculated using psychrometric law, defined as:

$$\Psi = - \frac{RT}{v_w M_w} \ln (RH) \quad \text{Equation 6:}$$

The R is universal gas constant, 8.3148 J/(mol·K), T is the absolute Temperature in Kelvin (K), M_w is the Molar mass of water, 0.018015 kg/mol, v_w the specific volume of water (inverse of the density of water at the specified temperature), and Relative Humidity (RH), dimensionless, expressed as a fraction between 0 and 1 and expressed as:

$$RH (\%) = \frac{Pv^{air}}{Pv^{sat}} \times 100 \quad \text{Equation 7}$$

where Pv^{air} is the Actual Vapor Pressure of air, and Pv^{sat} is the Saturation Vapor Pressure, in Pa/kPa.

For the drying process, the fibres were pre-soaked in seawater for 48 hours and then dried with tissue paper, resulting in initial water contents (w) of 143.32% and 125%. The 143.32% water content corresponded to the first scenario, where the fibres were bundled, while the 125% water content corresponded to the second scenario, where the fibres were separated. It is worth to say that the same fibres used for the bundled

configuration measurements were then used for the separated one, in order to always test fibres with same lengths and diameters. In both cases, the fibres were oven-dried at 50 °C for 24 hours. A 0.21 g sample was placed in plastic cups for measurement (*Figure 17b*), with suction readings taken every 6 hours. *RH* in drying process (*Figure 17c*) was monitored using the DS1923-F5 IButton sensor to ensure accurate environmental control (*Figure 17b* and

Figure 18).

Total suction (Ψ) was determined using the WP4C, and the resulting data were fitted using the Romero and Vaunat model [48], a modification of the van Genuchten model [49], which assumes that the void ratio remains constant during both processes, as expressed below:

$$S_r = C(s) \left(\frac{1}{1 + (\alpha s)^n} \right)^m \quad \text{Equation 8}$$

$$C(s) = 1 - \left(\frac{\ln \left[1 + \frac{s}{a} \right]}{\ln(2)} \right) \quad \text{Equation 10}$$

In this model, S_r represents the degree of saturation, while $C(s)$ is a function used to adjust the curve in the higher suction range. The parameter $1/\alpha$ corresponds to the air entry value, n relates to the slope of the curve, and m indicates the residual degree of saturation. Parameter a is considered the maximum suction at which $S_r=0$.

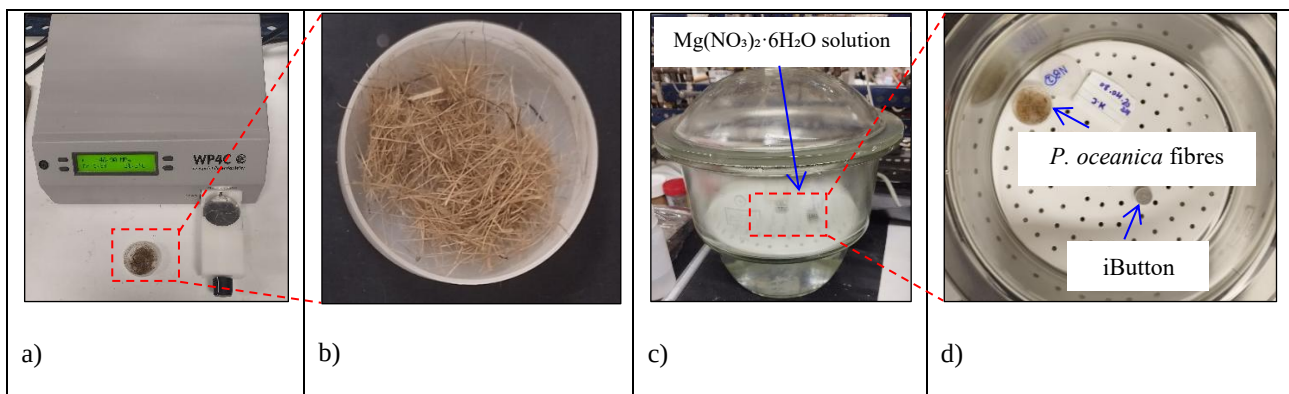


Figure 17: a) Closed chamber with NaCl solution, b) *P. oceanica* balls, and IBUTTON, c) WP4C; and d) *P. oceanica* ball fibres.

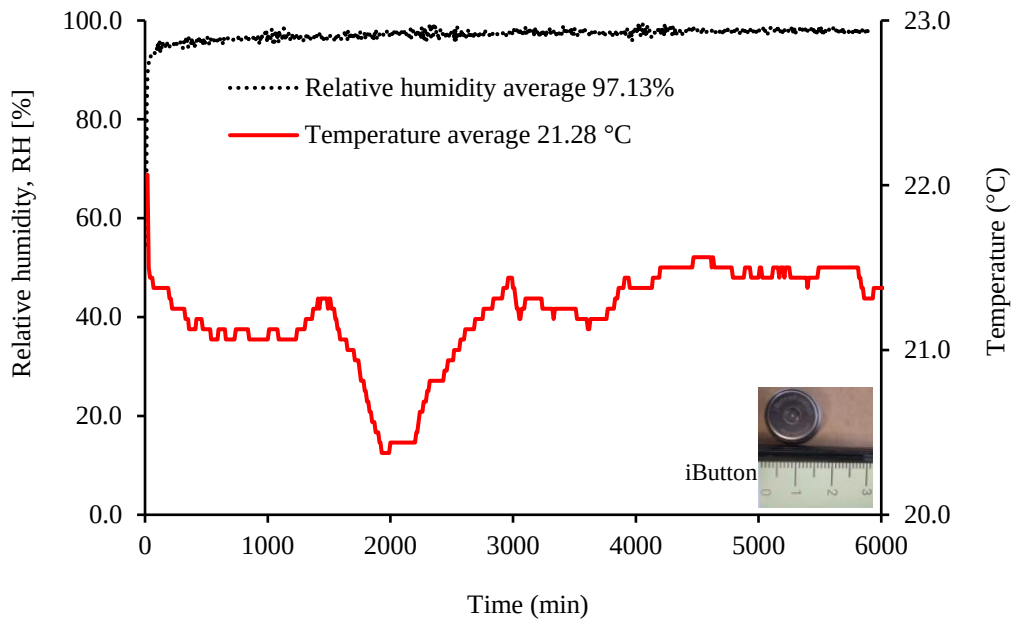


Figure 18: IBUTTON Sensor Measurement of humidity and temperature, for wetting paths.

4.6 Mixture preparation and testing

Mixtures with cement dry mass equal to the 16% of the dry mass of the sediment were prepared for this study, including the reference sample (DS16T) and fibre-reinforced samples with 1% *Posidonia* fibres in air-dried (DS16T1FAD) and pre-soaked (DS16T1FPS) conditions.

The cement was first mechanically mixed, using a spatula, with the dredged sediment for at least 3 minutes and anyway until ensuring a homogeneous mixture (by visual observation). Only the natural gravimetric water content of the sediment (i.e. $w = 71.08\%$) was used to trigger the hydration reactions in the cement. Then, the mixture was spread in a tray and the *Posidonia Oceanica*'s fibres were added and mixed for an additional 3 minutes, with a spatula, to ensure a uniform and random distribution.

The material was placed into polycarbonate moulds (38 mm diameter and 76 mm height) in three layers to minimize air entrapment, and each layer was tapped 50 times to reduce air bubbles following the Japanese Geotechnical Society procedure [69]. After casting, the specimens were cured under controlled laboratory conditions (i.e. $T = 22^{\circ}\text{C}$) beneath marine water for 7 and 28 days.

Unconfined compression tests were carried out on cured samples in accordance with standard ASTM D2166 [70] and by using a displacement rate of 0.5 mm/min. All specimens had height/diameter (76mm / 38mm) ratio equal to 2 and a fixed diameter of 38 mm (. Small-strain stiffness was assessed by ultrasonic pulse

velocity (UPV) measurements performed using a couple of 200 kHz transducers positioned at the plane ends of the cured specimens, in accordance with ASTM C597-16 [71].

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Jafar Karimiazar: paper conceptualization, formal analysis, writing original draft, visualization, methodology, data curation, image-based analysis and statistical evaluation, all experimental work, data collection, analysis, and elaboration. **Enrique Romero:** paper conceptualization, methodology, validation, formal analysis, investigation, sources, writing – review & editing, visualization, supervision, project administration, funding acquisition. **Rossella Petti:** validation, formal analysis, writing –review & editing, visualization. **Joel Torres-Serra:** validation, data curation, visualization, MATLAB programming. **Alessandro Fraccica:** data curation, visualization, review & editing. **Gioacchino (Cino) Viggiani:** paper conceptualization, data curation, review & editing, visualization. **Gustavo Pinzón:** paper conceptualization, image-based analysis and statistical evaluation, investigation, data curation, visualization. **Claudia Vitone:** paper conceptualization, methodology, validation, formal analysis, investigation, sources, writing – review & editing, supervision, project administration, funding acquisition.

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