

Hydro-mechanical behaviour of bio-cemented sediments reinforced with *Posidonia Oceanica* fibres

J. Karimiazar¹, E. Romero^{2,3}, R. Petti¹, J. Torres-Serra³, A. Fraccica⁴, C. Vitone¹

¹Politecnico di Bari, DICATECh, Bari, Italy

²Universitat Politècnica de Catalunya, Barcelona, Spain.

³International Centre for Numerical Methods in Engineering, Barcelona, Spain

⁴Istituto Superiore per la Protezione e la Ricerca Ambientale, ISPRA, Italy

ABSTRACT: The reuse of dredged or waste sediments in geotechnical engineering aligns with sustainability goals. However, these sediments often exhibit high compressibility upon loading, significant shrinkage upon drying, and low shear strength, necessitating effective stabilisation and reinforcement strategies. At the same time, natural lignocellulosic fibres, such as *Posidonia Oceanica* (PO), are well known for their mechanical benefits, yet their influence on key hydraulic properties, including water retention properties and pore structure, remains insufficiently explored. This study investigates the hydro-mechanical performance of dredged sediments (DS) treated with marine-derived biomaterials: mussel shell (MS) powder as a partial cement (T) substitute, and PO fibres for hydro-mechanical reinforcement. Three mixtures were tested on DS treated with: (i) 12% w/w cement and 4% w/w MS powder (DS12T4MS), (ii) 12% w/w cement, 4% w/w MS powder, and 1% w/w PO fibres (DS12T4MS1PO), and (iii) 16% w/w cement alone (DS16T). The water retention curve was determined with a chilled-mirror dewpoint psychrometer, while microstructural changes were assessed using scanning electron microscopy (SEM). Results show that MS powder improves structural densification of the mixture by filling macropores, increasing shear strength and the air-entry value (AEV), and consequently enhancing the water retention capacity at low suctions. In contrast, PO fibres, due to their lumen-rich morphology, induce an increase in macropores that facilitates their desaturation, and decreases the AEV. The combined use of MS and PO offers complementary benefits, enabling performance-based design of sediment composites tailored to specific hydro-mechanical requirements. This contributes to advancing sustainable ground improvement solutions using marine waste materials.

Keywords: Posidonia fibres; Soil water retention curve SWRC; Dredged sediment; Shells; Soil improvement

1 INTRODUCTION

Unsaturated soil mechanics has become increasingly important in geotechnical engineering because most natural and engineered earth structures undergo degree of saturation changes during their service life while interacting with the atmosphere. Partially saturated states, described by the soil–water retention curve (SWRC), influence shear stiffness, shear strength, and compressibility upon loading and hydraulic paths (Fredlund and Rahardjo, 1993). When soils are stabilized for engineering applications such as embankments, dikes, subgrades, or waste barriers, their long-term performance is governed not only by cementation-induced bonding but also by their hydraulic response under unsaturated conditions. Understanding this combined effect is therefore essential for reliable design (Sollecito et al., 2019). Dredged sediments (DS) pose a significant challenge for reuse. In Europe alone, marine environments, rivers, and lakes produce more than 200 Mm³/year of sediment (SedNet, 2011). These materials typically exhibit high initial water content, low permeability, and high compressibility, making them unsuitable for direct use in construction.

Cement stabilization has been widely employed to improve its strength and durability through hydration and pozzolanic reactions (Horpibulsuk et al., 2004, Wang et al., 2022, Federico et al., 2015). Previous studies showed that shear strength, shear stiffness, and compression characteristics depend strongly on cement content, curing time, and curing environment (i.e. relative humidity and temperature) (Spagnoli et al., 2022). However, these investigations were conducted under laboratory conditions without measuring or controlling suction, leaving the hydraulic behaviour of stabilized dredged sediments insufficiently explored. In recent years, sustainable alternatives to cement have attracted attention. Mussel shell (MS) powder, a biogenic calcium carbonate from aquaculture waste, serves as an eco-friendly cement substitute that reduces carbon emissions and enhances hydration. Its fine particles act as nucleation sites and may partially dissolve under alkaline conditions, releasing calcium ions that sustain C–S–H formation. Simultaneously, MS improves particle packing and pore filling, resulting in a denser and more compact matrix (Petti et al., 2024). In addition, plant source fibres such as *Posidonia*

Oceanica (PO) provide a bridging effect between soil particles, improving ductility and reducing brittle failure typically observed in cement-stabilized soils (Allègue et al., 2015). While many researchers have examined the mechanical benefits of cement substitutes and plant-based fibre reinforcement, little attention has been given to their influence on unsaturated hydro-mechanical behaviour. Also, the combined effect of biogenic calcium carbonate substitution and cement on the SWRC and pore structure evolution of stabilized fine-grained soils remains largely unexplored. This study addresses these gaps by investigating the unsaturated hydraulic and microstructural behaviour of dredged sediments stabilized with: (i) 16% cement, (ii) 12% cement + 4% mussel shell powder (MS), and (iii) 12% cement, 4% MS and 1% PO fibres. Soil–water retention curves were determined along drying paths, and microstructural features were examined using scanning electron microscopy (SEM). The results provide insight into how sustainable materials alter water retention and microstructure, thereby enhancing the role of unsaturated soil mechanics in sustainable ground improvement.

2 EXPERIMENTAL WORK AND METHODS

2.1 Dredged sediment, Mussel shell, PO fibres

Figure 1a shows the sediment that was dredged from Taranto, Italy, and Figure 1b shows *Mytilus galloprovincialis* shells, oven-dried (105 °C for 48 h), crushed, and sieved (through the ASTM No. 230 sieve) to obtain a powder with uniformity coefficient $C_u = 2.21$ and median particle size $D_{50} = 6.32 \mu\text{m}$, Figure 1d. In addition, Figure 1c presents PO fibres balls taken from shorelines in south of Italy and air-dried for three months (~60% air relative humidity RH, final water content of 18%). Fibre geometry, analyzed using ImageJ[®] and MATLAB[®], showed that fibre balls with 40–65 mm diameter contain fibres predominantly 10.1–25 mm long (Karimiazar et al., 2025), an optimal range previously identified for reinforcing cement-stabilized sediments (Karimiazar et al., 2024).

Figure 1d depicts the grain size distribution of DS taken from the Port of Taranto (Cotecchia et al., 2021). The DS has an initial water content of 71.08% and is classified as silty clay (30.4% clay, 63.8% silt; AGI, 1994) of high plasticity (CH). Atterberg limits were determined on 300 g of untreated sediment following ASTM D4318, with liquid and plastic limits measured in triplicate.

2.2 Sample preparations

The DS was treated using an environment-friendly binder composed of 16% blast furnace slag cement 32.5N, UNI EN 197-1 (mixture DS16T), as shown in

Figure 2a. An alternative mix (DS12T4MS) was prepared by adding 12% blast furnace slag cement with 4% mussel shell powder in a 1:3 replacement cement-shell ratio (Figure 2b, i.e., the substitution ratio was suggested by (Petti et al., 2024)). A third formulation (DS12T4MS1PO) introduced 1% PO air-dried fibres (with lengths between 10.1 and 25 mm), into the DS12T4MS matrix, forming a fibre-reinforced composite (FRCS) (Figure 2c). All percentages refer to the sediment's dry weight. The sediment's natural water content was used for hydration, without the addition of external water. Cement and mussel shell powder were first blended into the sediment first, then fibres were mixed by hand for 3 minutes to achieve even distribution. Uniform fibre dispersion was achieved by gradually adding and hand-mixing the fibres to promote random orientation. Visual inspection and micro X-ray tomography confirmed a homogeneous distribution without clustering or preferential alignment that could affect the soil–water retention behaviour (Fraccica et al., 2024). Prepared slurry samples were put in a plastic container, then tapped 50 times following the Japanese standard protocol (JGS, 2000) to eliminate air bubbles. Samples were cured in seawater for 28 days.

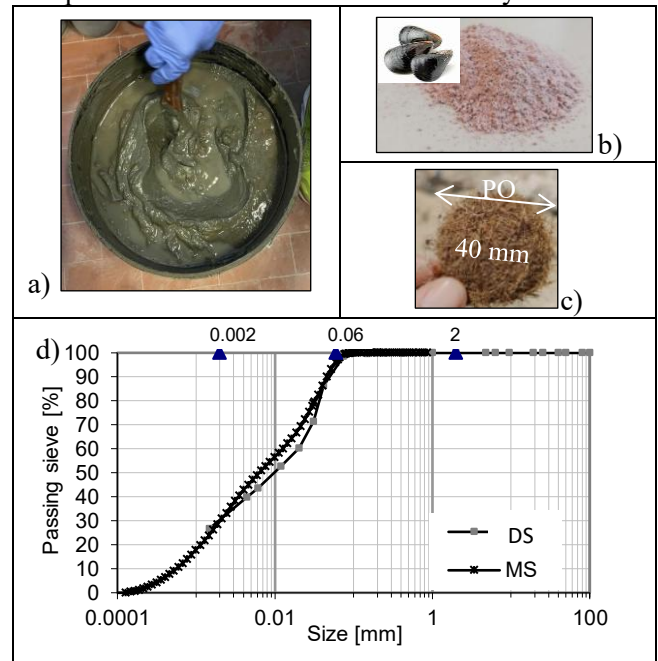


Figure 1. Raw materials: a) Sediment, b) process for mussel shell powder preparations, c) PO fibres, and d) Grain size distribution of the sediment (DS) and mussel shell powder (MS)

2.3 Soil water retention curve

After 28 days of curing, 1 cm³ samples were progressively dried to 50% RH, and their total suctions were measured with a WP4C dew-point potentiometer following ASTM D6836-02 (2008) (ASTM, 2008). Based on the psychrometric law, this method links pore-air RH (vapour) to the liquid soil water energy state, with total suction (Ψ) defined as:

$$\Psi = -\frac{RT}{v_w M_w} \ln(RH) \quad (1)$$

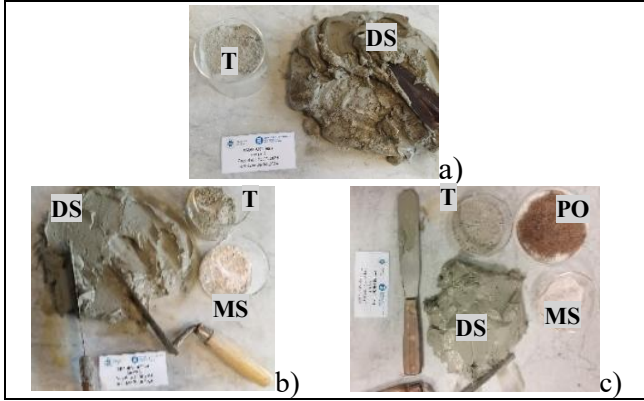


Figure 2. Preparation of the three mixtures: a) DS16T, b) DS12T4MS, c) DS12T4MS1PO

where T is absolute temperature, R the universal gas constant, M_w the molecular mass of water and v_w the specific volume of water (inverse of the density of water at the specified temperature). Total suction (Ψ) was fitted using the Romero and Vaunat expression (Romero and Vaunat, 2000), a modified van Genuchten formulation (Van Genuchten, 1980) with linear variation in a semi-log plot in the high Ψ domain. The expression as a function of the degree of saturation S_r is given as:

$$S_r = C(s) \left(\frac{1}{1+(as)^n} \right)^m \quad (2)$$

$$C(s) = 1 - \left(\frac{\ln\left[1+\frac{s}{a}\right]}{\ln(2)} \right) \quad (3)$$

In this model, $1/\alpha$ is associated with the air-entry value (AEV), n governs the slope at the inflection point, and m relates to residual saturation. The parameter $a=1000$ MPa sets the maximum suction at which S_r tends to zero.

3 RESULTS

3.1 Soil water retention

The soil–water retention curves (SWRCs) upon drying of the three mixtures DS16T, DS12T4MS, DS12T4MS1PO are shown in Figure 3. In the figures, e_0 denotes the initial void ratio and w_0 the initial water content of the mixtures. Comparing DS16T and DS12T4MS with similar shape, the second mixture presented a higher AEV, indicating higher degrees of saturation for equivalent total suctions. Cement replacement with mussel shell powder promoted the formation of additional cementitious products and a filler effect, leading to improved pore filling and enhanced water retention capacity. At high total suctions, both curves converged, indicating that the residual degree of saturation was not greatly influenced by cement substitution. The mixture reinforced with *Posidonia* fibres (DS12T4MS1PO)

showed a distinct response. Its AEV decreased, and the fitted $1/\alpha$ parameter was lower than those of DS16T and DS12T4MS (Table 1). This behaviour can be attributed to the lumen structure of the natural fibres, which created additional connected macro-voids and facilitated easier desaturation (Bordoloi et al., 2017).

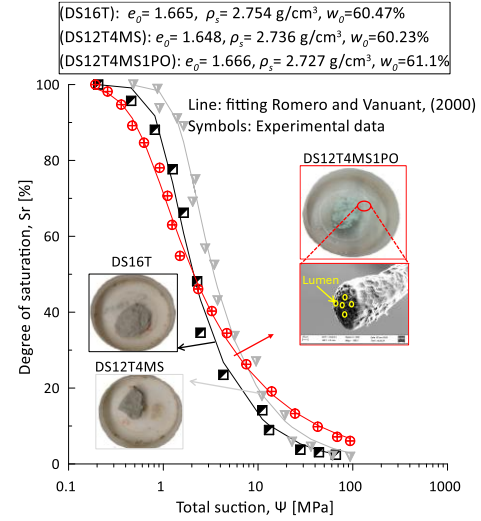


Figure 3. Soil–water retention curves (SWRCs) and fittings for DS16T, DS12T4MS, and DS12T4MS1PO

Table 1. Fitting parameters for all mixtures

Mixtures	$1/\alpha$ (MPa)	n	m	e_0
DS16T	0.94	4.30	0.20	1.665
DS12T4MS	1.55	4.30	0.20	1.648
DS12T4MS1PO	0.57	2.67	0.20	1.666

3.2 SEM analyses

SEM analyses were conducted on freeze-dried specimens, in liquid nitrogen and coated with gold. A Zeiss Gemini Sigma 300 VP FE-SEM was used to examine microstructural features. SEM observations reported by (Petti et al., 2024), concerning the microstructural study of mixtures of the same sediment stabilized with mussel shell powder and reduced cement content, highlighted that mussel shell powder acts as a filler and nucleation agent, promoting the formation of C–S–H honeycomb structures and pore filling that enhanced water retention capacity. This confirms that MS powder not only acts as a physical filler but also chemically participates in cement hydration reactions by enhancing nucleation and promoting secondary calcium-silicate-hydrate formation. This role is also confirmed by the SWRCs (Figure 3), where it appears evident that cement replacement with mussel shell powder (DS12T4MS) increases the AEV and enhances water retention compared to DS16T. Conversely, the addition of PO fibres (DS12T4MS1PO) tends to decrease the AEV and leads to faster desaturation, as confirmed by SEM observations of the sediment matrix treated with shell powder, PO fibres, and reduced cement content (Figure 4), where the fibre lumen introduced connected and open channels to the atmosphere. Therefore, the

fibres tend to create preferential pathways for air entry and facilitate water loss in the low total suction zone, where both the fibre lumen and the fibre–matrix interface generate additional desaturation pathways. Thus, while mussel shell powder improves water retention by densifying the matrix, the fibres modify it, creating larger porosity systems due to the lumens and more possible connected porosities which boost the soil–atmosphere interactions.

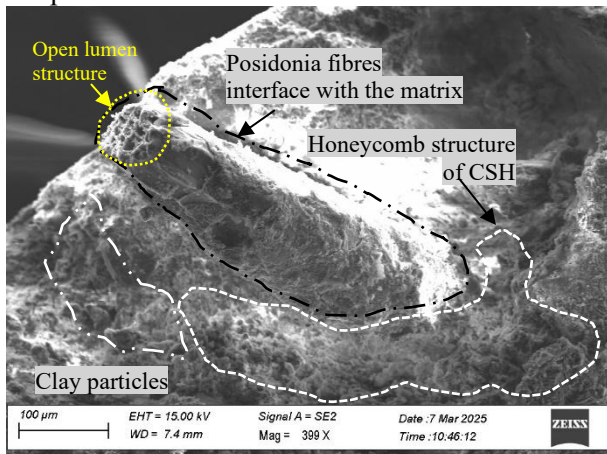


Figure 4. SEM image of DS12T4MSIPO mixture

4 CONCLUSION

This study shows the potential of marine biowaste in improving dredged sediments, which are typically unsuitable for reuse due to their high compressibility and low shear strength. Partial substitution of cement with mussel shell powder enhanced the microstructure by acting as both filler and nucleation site. This promoted C–S–H gel formation, refined the pore system, and increased the air-entry value, thereby improving water retention capacity. By contrast, the addition of *Posidonia* fibres introduced lumen voids and weak fibre–matrix interfaces, creating macro-pores preferential desaturation pathways and reducing water retention properties in the low total suction domain (below 10 MPa). These contrasting yet complementary effects demonstrate how mussel shell powder and *Posidonia* fibres can be combined to adjust hydraulic properties and support sustainable sediment stabilization. The durability of *PO* fibres will be investigated in future work through long-term seawater curing.

5 ACKNOWLEDGEMENTS

Co-funded by the European Union. Projects 101114177 LIFE22-ENV-IT-LIFE GL4S and PID2022-141429OB-I00 MICIU/AEI/10.13039/501100011033.

6 REFERENCES

- Allègue, L., Zidi, M., Sghaier, S. 2015. Mechanical properties of *Posidonia oceanica* fibers reinforced cement, *Journal of Composite Materials* **49**, 509-517.

- ASTM, D. 2008. Standard test methods for determination of the soil water characteristic curve for desorption using a hanging column, pressure extractor, chilled mirror hygrometer, and/or centrifuge. *D6836*.
- Bordoloi, S., Hussain, R., Garg, A., Sreedeeep, S., Zhou, W.-H. 2017. Infiltration characteristics of natural fiber reinforced soil, *Transportation Geotechnics* **12**, 37-44.
- Cotecchia, F., Vitone, C., Sollecito, F., Mali, M., Miccoli, D., Petti, R., Milella, D., Ruggieri, G., Bottiglieri, O., Santaloia, F. 2021. A geo-chemo-mechanical study of a highly polluted marine system (Taranto, Italy) for the enhancement of the conceptual site model, *Scientific Reports* **11**, 4017.
- Federico, A., Vitone, C., Murianni, A. 2015. On the mechanical behaviour of dredged submarine clayey sediments stabilized with lime or cement, *Canadian Geotechnical Journal* **52**, 2030-2040.
- Fraccica, A., Romero, E., Fourcaud, T. 2024. Effects of vegetation growth on soil microstructure and hydro-mechanical behaviour, *Géotechnique*, 1-15.
- Fredlund, D.G., Rahardjo, H. 1993. *Soil mechanics for unsaturated soils*, John Wiley & Sons.
- Horpibulsuk, S., Bergado, D., Lorenzo, G. 2004. Compressibility of cement-admixed clays at high water content, *Geotechnique* **54**, 151-154.
- JGS 2000. Practice for making and curing stabilized soil specimens without compaction. JGS Tokyo.
- Karimiazar, J., Vitone, C., Romero, E., Torres-Serra, J., Petti, R., Fraccica, A. 2025. Using *Posidonia Oceanica* Fibres for the Mechanical Improvement of Sediments. *IOP Conference Series: Earth and Environmental Science*. IOP Publishing, 012125.
- Karimiazar, J., Vitone, C., Romero Morales, E.E., Petti, R., Torres Serra, J., Fraccica, A. 2024. Toward sustainable sediment reinforcement: first results on the characterisation of biological fibres of *Posidonia oceanica*. *Atti dell'Incontro Annuale dei Ricercatori di Geotecnica: IARG2024*. Edizioni AGI, IV-14-IV-19.
- Petti, R., Vitone, C., Marchi, M.I., Plötze, M., Puzrin, A. 2024. Use of shells for the mechanical stabilisation of sediments: a valuable geomechanical perspective? *Geotechnique*, 1-20.
- Romero, E., Vaunat, J. 2000. Retention curves of deformable clays. *Experimental evidence and theoretical approaches in unsaturated soils*. CRC Press.
- SEDNET. 2011. Dredging and Sediment Management: European Sea Port, *7th International SedNet Conference*, Venice, Italy. Thetis S.p.A.
- Sollecito, F., Vitone, C., Miccoli, D., Plötze, M., Puzrin, A.M., Cotecchia, F. 2019. Marine sediments from a contaminated site: Geotechnical properties and chemo-mechanical coupling processes, *Geosciences* **9**, 333.
- Spagnoli, G., Romero, E., Fraccica, A., Arroyo, M., Gómez, R. 2022. The effect of curing conditions on the hydromechanical properties of a metakaolin-based soilcrete, *Géotechnique* **72**, 455-469.
- van Genuchten, M.T. 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils, *Soil science society of America journal* **44**, 892-898.
- Wang, W., Kang, H., Li, N., Guo, J., Girma, D.Y., Liu, Y. 2022. Experimental investigations on the mechanical and microscopic behavior of cement-treated clay modified by nano-MgO and fibers, *International Journal of Geomechanics*, **22**, 04022059.