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The valorisation of marine waste: first results from GL4S project

Marzieh Kianimehra, Rossella Pettib, Claudia Vitonec
aPhD student, bAssistant Professor, cFull Professor: Politecnico di Bari-Department of Civil, Environmental, Land, Construction and Chemistry (DICATECh)-Bari-Italy. m.kianimehr@phd.poliba.it, rossella.petti@poliba.it, claudia.vitone@poliba.it.

ABSTRACT: Environmental pressures and the need for sustainable waste management solutions pose new challenges for geotechnical engineering, particularly in the context of rapid climatic and social transformations. This study addresses the disposal challenges associated with two high-impact marine by-products: dredged sediments from ports and mussel shells from aquaculture. The objective is to present some preliminary geotechnical results from a five-year project, GREENLIFE4SEAS (GREen ENgineering solutions: a new LIFE for SEdiments And Shells, GL4S), funded under the European Union's LIFE programme. Currently, sediments are systematically dredged to ensure port navigability and/or to remove contaminants (approximately 200 million m³ of sediments are dredged annually in Europe, SedNet). These materials are often treated as waste and disposed of in confined disposal facilities, resulting highly impacting resource expenditure for their management. At the same time, the global production of marine bivalves for human consumption is more than 15 million tonnes per year mussel shells, therefore, represent another highly impactful marine by-product. Given their substantial quantities and composition (95% $CaCO_3$), mussel shells are difficult to compost and present long-term disposal challenges. In this context, GL4S aims to develop sediment-based mixtures with low binder content by incorporating mussel shell powder. These mixtures will be used to produce and install industrial prototypes in four different European ports. This paper will present the preliminary results of the project achieved through collaboration among universities, research centres, and industrial partners. In particular, from the multiscale and multidisciplinary characterisation carried out on both natural sediments and mechanically treated ones to define the mixtures for the first prototypes, this paper will present some of the results obtained from the geomechanical investigations.

KEYWORDS: Sustainable geotechnics, Dredged sediments, Mussel shells, Mechanical treatment, Environmental resilience, Biogeotechnics, Marine geotechnics.

1 INTRODUCTION

The reuse of marine waste materials for the development of innovative products is a rapidly growing area of research, driven by its relevance to environmental sustainability and alignment with several of the United Nations' 2030 Sustainable Development Goals (SDGs). In this context, the LIFE programme has recently funded a project led by the Polytechnic University of Bari, titled GREENLIFE4SEAS (GREen ENgineering solutions: a new LIFE FOR SEdiments And Shells). The project aims to transform two high-impact marine waste streams dredged sediments and mussel shells into prototypes of industrial products. Both waste types pose significant environmental challenges due to their large-scale production and the complexity of their disposal. Across Europe, an estimated 200 million cubic metres of sediments are dredged annually (SedNet, 2011). In Italy and Greece, the two EU Member States involved in the project approximately 50 million and 30 million cubic meters, respectively, are dredged each year. Notably, about 20% of this material exceeds regulatory thresholds for heavy metals and/or organic pollutants (Palumbo, 2007). Even when uncontaminated, marine sediments are considered complex geomaterials due to their highly variable consistency; the presence of shells, fossils, and diatoms; and the diversity of interstitial fluids and naturally occurring organic matter, which are heterogeneously distributed (Cotecchia et al., 2021; Singh et al., 2023). These factors are well known to significantly affect the geomechanical behaviour of soils (e.g., Vitone et al., 2020; Sollecito et al., 2022; Di Maio, 1996; Gajo & Maines, 2007; Jang & Santamarina, 2016; Yadav et al., 2024) On the other hand, global marine bivalve production for human consumption exceeds 15 million tons annually, accounting for approximately 14% of total aquaculture output (Wijsman et al., 2019). Europe is the second-largest mussel producer worldwide, generating around 465,000 tons per year, with Italy and Greece ranking among the top ten countries for mussel and oyster production (FAO-Fishstat, 2016). This activity results in the accumulation of large quantities of mussel shell waste, which is non-biodegradable and difficult to compost, and is composed of more than 95% calcium carbonate. The GREENLIFE4SEAS project, GL4S, builds upon previous research conducted at the Polytechnic University of Bari (Petti et al., 2024; Roque et al., 2021; Patent No. 102021000025103) and ETH Zurich, which demonstrated, at the laboratory scale, the effectiveness of a novel mechanical stabilisation treatment involving hydraulic binders partially replaced with mussel shell powder prepared without calcination. The shells, derived from the common *Mytilus Galloprovincialis* species, consist primarily of calcite (~80%), with a significant proportion of aragonite (15–20%), as well as traces of quartz and organic matter. This biomaterial has proven to be an innovative and sustainable additive, capable of reducing the cement content required to achieve target mechanical performance in sediment stabilisation (Petti et al., 2024). The biogenic calcium carbonate in mussel shells is notably more reactive and susceptible to decomposition than its lithogenic counterpart (Zamanian et al., 2021), owing to the distinctive morphology and spatial arrangement of calcite and aragonite crystals, combined with embedded organic matter. A representative feature is their characteristic "brick-and-mortar" microstructure (see Fig. 1), which contributes to enhanced reactivity. These distinctive properties render mussel shells particularly reactive in chemical hydration processes involving sedimentary silicates and the mineral phases of cement. The effectiveness of this approach was validated through a multiscale investigation that examined the geomechanical, physical-chemical, and hydraulic behaviour of sediment-based mixtures in which mussel shell powder partially replaced cement. The performance of these mixtures was compared to that of control samples composed solely of sediments and cement. The research identified a threefold role of mussel shell powder even without calcination, but after thermal treatment at 105°C for 48 hours. i) With a fine particle size (D_{50} = 6.32 μm; Cu = 2.213), the powder acts as a micro-filler, improving particle packing. ii) Its higher specific surface area compared to cement promotes nucleation of hydration products. iii) The partial decomposition of biogenic carbonates enhances secondary pozzolanic reactions, refining the microstructure and increasing strength (Petti et al., 2024). Moreover, the mechanical behaviour of these mixtures aligns with well-established soil mechanics principles, confirming their compatibility with standard geotechnical models. This paper presents selected findings from the GREENLIFE4SEAS project, focusing on three main research areas including: i) geomechanical characterisation of natural dredged sediments sourced from the ports of Bari, Barletta, La Spezia, and Piraeus; ii) ongoing optimization of industrial-scale production processes for mussel shell powder, aiming to ensure consistent quality, particle size distribution, and environmental sustainability; iii) optimization of mussel shell powder utilization as a partial replacement for cement, with the objective of assessing the behaviour of treated sediments. These geotechnical results, obtained as part of the multidisciplinary characterisation developed through collaboration with universities, research centres, and industrial partners involved in the project, form the basis for the calibration of treated sediment mixtures according to: (i) the geotechnical properties of the sediments to be treated, and (ii) the performance requirements of the prototype to be produced. This step is essential for scaling up the process of on-site production of final construction materials directly at the participating ports. Ultimately, the findings contribute to the broader goal of the GREENLIFE4SEAS project, transforming dredged sediments and mussel shell waste into sustainable, high-performance construction materials while promoting circular economy practices in coastal and port engineering.

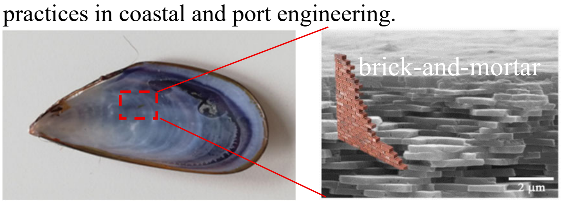

Figure 1. Typical "brick-and-mortar" microstructure of mussel shells.

2 THE GREENLIFE4SEAS PROJECT

GREENLIFE4SEAS (GL4S, https://greenlife4seas.poliba.it) is a five-year European project coordinated by the Polytechnic University of Bari and funded by the EU LIFE Programme. It brings together nine European partners in a triple helix consortium of academia, public institutions, and private companies. By integrating expertise across sectors, GL4S aims to become a European benchmark for the sustainable management of dredged sediments and mussel shells. These waste materials will be transformed into raw materials for industrial products (Fig. 2), including prototypes such as breakwaters, paving blocks, and mass stabilisation models, to be installed in four partner ports: Bari, Barletta, La Spezia (Italy), and Piraeus (Greece). The project includes the design of two pilot processing plants: i) a fixed plant for producing mussel shell powder and aggregates; ii) a mobile plant for on-site manufacturing of paving blocks and breakwaters. Regulatory and procedural oversight is provided by ISPRA, in collaboration with researchers from the Polytechnic University of Bari and CNR (IRSA and IRET), covering geotechnical, environmental, chemical, and biological disciplines. The project focuses on sourcing, preparing, and experimentally characterising raw materials and mixtures, with optimized mix designs tailored to specific technical goals. Figure 2 illustrates the overall workflow of the GREENLIFE4SEAS project, summarizing the sequence from raw material collection to the production of industrial prototypes. The diagram highlights the main processing lines, the fixed plant for mussel shell powder production, the mobile plant for sediment-based prototype manufacturing, and the multiscale laboratory investigations supporting mixture optimisation.

This figure is relevant to the present study because it contextualises the preliminary geotechnical results reported in this paper within the broader project framework. Specifically, the sediment characterisation and the first stabilisation tests represent the initial phase of the mixture design process prior to full-scale prototype production. Another project line targets organically contaminated sediments from La Spezia and Bari, which will undergo in-situ bioremediation, followed by mechanical stabilisation and reuse within the port infrastructures.

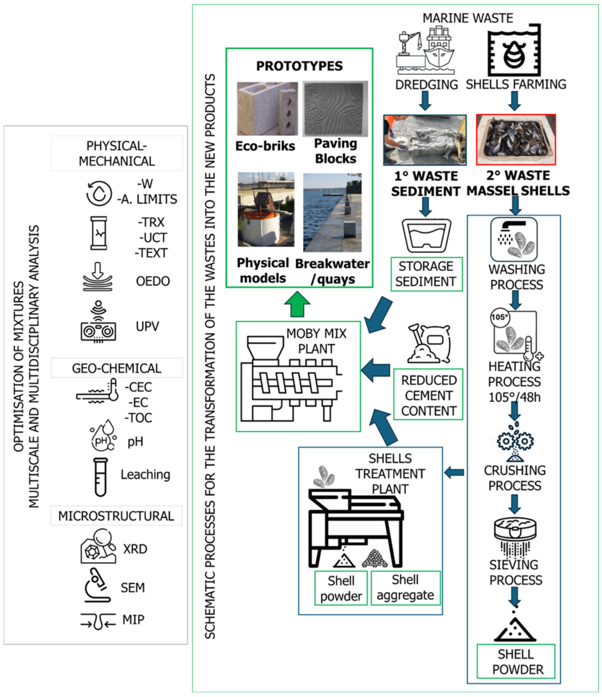

Figure 2. Project layout GREENLIFE4SEAS: GREen Engineering solutions: a new LIFE FOR SEdiments And Shells.

3 PRELIMINARY RESULTS

3.1 *SEDIMENTS FROM BARI, BARLETTA, LA SPEZIA AND PIRAEUS PORTS*

This section presents the preliminary results of the geotechnical characterisation of sediments collected from the ports of Bari, Barletta, La Spezia and Piraeus, i.e., the four sites involved in the GREENLIFE4SEAS project. The grain size distribution curves and plasticity properties of all sediments (Figures 3 and 4) reveal marked differences. As detailed in Table 1, the Bari (BS) sediment is classified, according to the USCS system, as a silty clay with sand and a high-plasticity clay (CH). In contrast, the Barletta (BTS) sediment is identified as a silty sand with clay while La Spezia (La Sp) and Piraeus (PS) sediments are sandy clay with silt with lower plasticity compared to Bari sediment. Based on organic matter content, the Bari sediment is categorized as medium-organic, while the Barletta, La Spezia and Piraeus sediments are considered low-organic, in accordance with ISO 14688-1/2. Water content values (W_0 in Table 1) were corrected for salinity following the approach proposed in the literature (BS 1377; Sollecito et al., 2019) and indicate higher values for the more organic and clay-rich Bari sediment (W_0= 102.4%), and lower values, around 40-50%, for the remaining three sediments. In addition, the four types of sediments were tested to determine their liquid limit (W_L) and plastic limit (W_P) using two methods: i) Standard procedure: conducted on the portion passing through ASTM No. 40 sieve; ii) Non-standard procedure: performed on the entire, unsieved material. The non-standard method was adopted to account for organic debris (e.g., algae and underwater vegetation) retained on the sieve, which significantly influences sediment plasticity, unlike inert particles (Roque et al., 2021). As shown in Figure 4, tests on the unsieved material resulted in higher values of both the liquid limit (W_L) and plasticity index (PI), generally reflecting the organic content's role in enhancing the sediment's water retention and deformability.

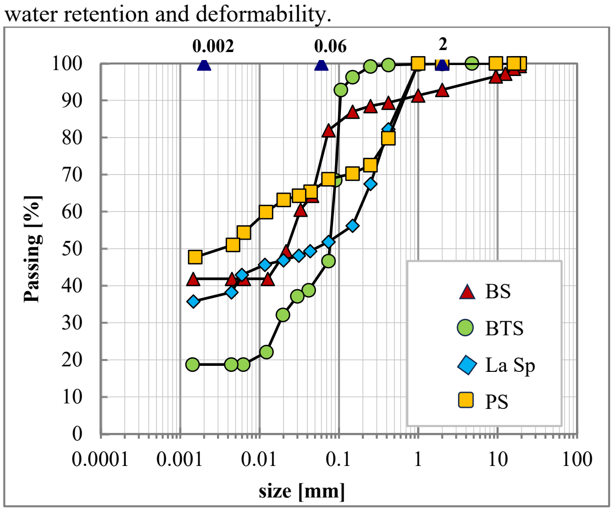

Figure 3. Grain size distribution of the samples of Bari (BS), Barletta (BTS), La Spezia (La Sp) and Piraeus (PS) sediments.

Since the GL4S project develops mixtures using sediments in their in-situ state without any pretreatment, evaluating plasticity on the full material matrix including organic components is essential for accurately assessing geotechnical properties and ensuring the reliability of engineered solutions. This justifies the use of the non-standard testing approach, which provides a more representative characterisation of the sediment's behaviour under natural conditions, particularly in marine environments where organic matter is prevalent. Additionally, this method allows for a better understanding of how organic debris interacts with mineral fractions, potentially affecting the long-term stability of sediment mixtures in applications such as harbour fills or reclamation projects. In addition, Figure 5 illustrates the results of one-dimensional compression tests (oedometer tests) on natural sediments from Bari, Barletta, La Spezia, and Piraeus, highlighting their compressibility under increasing effective stress. Bari sediment exhibits the highest initial void ratio (approximately 1.88 at low stress) with greater compressibility compared to Barletta, La Spezia, and Piraeus, which exhibit lower initial void ratios (around 1.00 at 10 kPa of vertical effective stress). All samples are nearly normally consolidated or lightly overconsolidated, with preconsolidation pressures around 100 kPa, suggesting minor past loading or desiccation effects.

Table 1. Table 1. Physical and index properties of the sediments: CF: clay fraction; A: activity index; W_L: liquid limit; PI: plasticity index; W_0: water content; OM: organic matter; NS: non-standard procedure.

	CF [%]	A [-]	W_{LNS} [%]	PI_{NS} [%]	W_0 [%]	OM [%]
Standard	ASTM D422	-	BS1377:2	-	ASTM D2216	ASTM D2974
Bari	41.9	1.24	87.8	52.2	102.4	6.38
Barletta	18.7	0.80	48.8	15.1	47.9	1.61
La Spezia	36.0	0.38	32.44	13.52	38.27	3.52
Piraeus	47.0	0.22	36.58	10.27	35.55	3.16

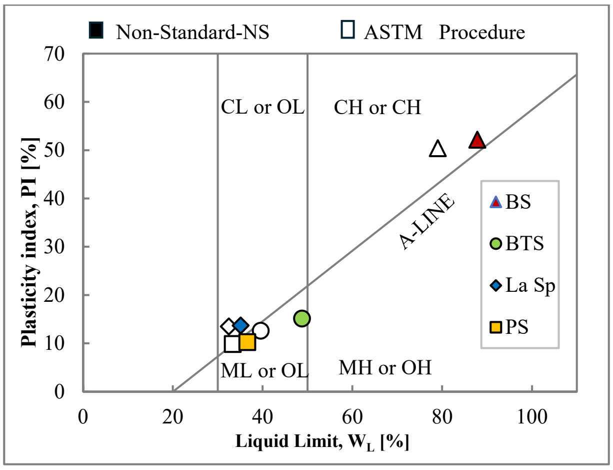

Figure 4: Casagrande plasticity chart representative the samples of Bari (BS), Barletta (BTS), La Spezia (La Sp) and Piraeus (PS) sediments.

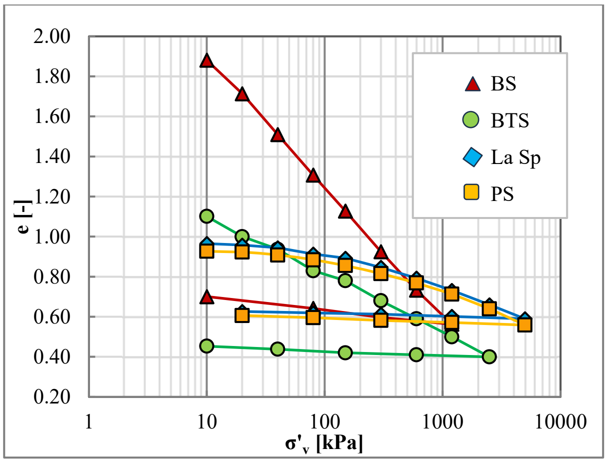

Figure 5: Oedometer results of Bari, Barletta, La Spezia and Piraeus sediments.

3.2 *Optimisation of Mussel Shell Powder*

To produce mussel shell powder, the shells were washed to remove external debris, air-dried, and thermally treated at 105°C for 48h, after which they were ground and sieved through a No. 230 (63µm) mesh. Petti et al. (2024) report experimental results obtained on mixtures of sediment from the port of Taranto mechanically treated with a binder solution in which a portion of traditional cement was replaced by powder derived from mussel shells through the described thermo-mechanical treatment. The authors indicate that needle-shaped aragonite crystals persist even after the imposed treatment and that the biogenic calcium carbonate from the shells acts as a booster in the hydration and cementation processes between sediment, cement, and water. Based on these findings, ongoing experiments aim to assess the feasibility of reducing the thermal treatment duration to support industrial-scale application. For this purpose, mussel shells were processed into powders after different thermal treatments: untreated (RT), and treated at 105°C for 3 hours, 9 hours, and 48 hours. These powders underwent thermogravimetric analysis (TGA) and total organic carbon (TOC) determination, calculated as the difference between total carbon and inorganic carbon (TIC), in accordance with DIN EN 15936. Additionally, the powders were used to prepare new mixtures with Taranto sediment and cement, currently undergoing chemical, physical, and geotechnical characterisation. As shown in Figure 6 and 7, TOC content and consistency index (CI) were evaluated as a function of treatment duration. Results indicate a decrease in organic matter loss with shorter heating times, and a negative impact on the consistency index (CI) was observed in mixtures containing powders treated for less than 48 hours. These results appear to confirm that 48 hours of thermal treatment of the shells represents the optimal duration, and this finding motivates further investigation into alternative treatment times that could optimize powder production while minimizing energy consumption and CO_2 emissions. At this stage of the project, no fixed threshold values of TOC or CI have been formally defined. However, previous studies (Petti et al., 2024) indicate that powders produced with sufficiently low TOC and a CI consistent with stable binder–sediment interactions are required to ensure effective reactivity. The results obtained here confirm that the 48h treatment yields TOC and CI values aligned with those conditions, whereas shorter treatments result in suboptimal performance. For this reason, the 48h thermal treatment is currently used as the reference condition.

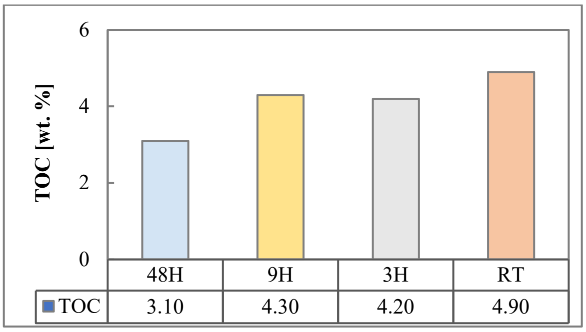

Figure 6. TOC values of the analysed powders subjected to different thermal treatment durations.

3.3 *Mussel Shell Mixtures and Control Mixtures-Unconfined Compressive Strength (UCS) test*

The mechanical stabilisation of the sediments was performed by defining the amount of additives as a percentage of the dry mass of the sediment (Ps). In other words, the binder content (cement or cement + mussel shell powder) was calculated relative to Ps so as to obtain the desired water-to-additive ratio, using only the natural water present in the sediment. Initially, each sediment was homogenised by mechanical mixing for 10 minutes. Then, the dry additives either cement alone or the bio-binder obtained by partially replacing cement with mussel shell powder were added and mixed for an additional 5 minutes at low speed (140 RPM). No additional water was added to the mixtures. The natural water content of each sediment was used as the only source of mixing water. The amount of cement or bio-binder was therefore calibrated with respect to the dry weight of sediment so that the ratio between the natural water content and the total additive mass was set to be equal to 4.8. This value had been previously identified in earlier studies on similar treatments (Petti et al., 2024; patent no. 102021000025103). The experimental mussel shell mixtures were prepared by replacing one-third of the cement content in the control mixtures (cement type I 52.5 R) with mussel shell powder treated at 105°C for 48 hours. Each produced mixture underwent a multiscale and multidisciplinary characterisation, and the following presents the first results concerning the water content and uniaxial compressive strength of the mixtures produced using sediment from Bari and Barletta with Portland cement (P) and mussel shell powder (MS) (BS16P5MS and BTS7.5P2.5MS, respectively), compared to their respective control mixtures (BS21P and BTS10P). The physical characterisation of the mixtures indicates that both mussel shell mixtures exhibited slightly lower water content than the control samples (BS16P5MS = 70%; BTS7.5P2.5MS = 36.8%; BS21P = 72.7%; BTS10P = 37%). In addition, Figure 8 presents the unconfined compressive strength (UCS) test results (ASTM D2166) on cylindrical specimens (d = 38 mm, h = 76 mm) after 28 days of curing in seawater. The data (Fig. 8) show that mixtures containing sediment, cement, and mussel shell powder achieved peak strength values comparable to those of the control mixtures, for both Bari and Barletta sediments.

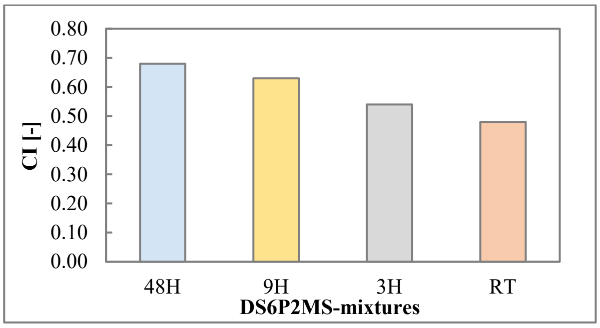

Figure 7. Consistency index (CI) of mixtures containing Taranto sediment-cement and mussel shell powder subjected to varying thermal treatments (48h, 9h, 3h and without thermal treatment RT).

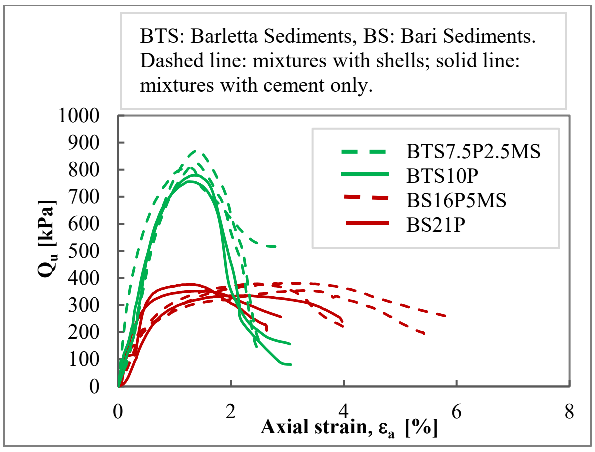

Figure 8: Unconfined Compression Strength (Q_u) – axial strain curves for mixtures prepared with sediments from Bari (BS) and Barletta (BTS). Dashed lines correspond to mixtures where mussel shell powder was used as a partial replacement for cement, while solid lines represent mixtures produced without shell powder.

In the case of the Bari sediment mixtures, the stress–strain curves of the mussel shell–cement formulations showed a less pronounced peak compared to the control ones, indicating a more ductile behaviour. In terms of stiffness, it seems that the bio-binder mixtures are slightly stiffer than the controls ones only when the Barletta sediments are used. Furthermore, despite having the same water-to-cement ratio and identical mixing procedures, the mixtures produced with Barletta sediment (which is characterised by higher sand content and lower plasticity) consistently exhibited higher compressive strength than those based on Bari sediment. For the ongoing activities, the same experimental procedures previously applied to the sediments from Bari and Barletta will also be adopted for the analysis for the sediments from La Spezia and Piraeus. These tests will investigate the mechanical and physical behaviour of the materials when stabilized with cement and mussel shell powder, allowing for a comparative evaluation of performance across all sediment categories.

3.4 *Mussel shell mixture and Control Mixtures- One-dimensional compression behaviour*

The behaviour of the stabilized sediments was also analysed in terms of one-dimensional compressibility, performed in accordance with ASTM D2435 on cylindrical specimens (diameter = 56 mm, height = 20 mm) after a 28-day curing period in seawater. Figures 9 and 10 present one-dimensional compression test results for mixtures produced using sediments from Bari and Barletta, stabilized with cement and mussel shell powder (BS16P5MS and BTS7.5P2.5MS, respectively), compared to their control mixtures (BS21P and BTS10P).

The results show that the stabilised mixtures with shells exhibit compression behaviour closely resembling that of their respective control mixtures, with comparable vertical effective stresses at yield (σ'_y). In particular, when Bari sediments are treated, the recompression index values, Cr, of the control mixtures are lower (0.012) than those of the bio-binder (0.024) based mixtures whereas similar compression index, Cc, values are recorded (1.10, 1.27). As for the unconfined compression tests, the efficacy of the shell-based treatment seems to be higher when the sediments from Barletta are used. In this case, it seems that, even the compression index of the biobinder mixtures (0.429) is, on average, lower than that of the control mixtures (0.482). For both the sediments it is observed that the shell-based mixtures have lower initial void ratios than the controls ones, confirming the higher pore filling capacity of the biobinder compared to just cement. Notably, the treated Barletta sediment, characterised by a higher sand content, exhibits both the highest yield stress and the greatest unconfined compressive strength, whether stabilized with cement alone or in combination with mussel shell powder. This behaviour is observed despite applying identical treatment procedures and water-to-binder ratios to the Bari sediment, which is finer, more plastic, and richer in organic matter. These results highlight the significant influence of sediment granulometry and composition on the mechanical response of stabilized materials, underlining the need for site-specific optimization in geotechnical applications. In the next phase, a comprehensive series of oedometer tests will be performed using the same water-to-binder ratio previously applied to the Bari and Barletta sediments, in order to thoroughly assess the consolidation behaviour of the remaining sediment types, La Spezia and Piraeus.

4 CONCLUSIVE REMARKS

This note presents the initial findings of the European GREENLIFE4SEAS project, funded under the LIFE program. The project involves a European triple-helix consortium and benefits from a wide-ranging partnership that brings together academic institutions, industry partners, and local and national public authorities. Its primary goal is to establish a European benchmark for sustainable management strategies of two high-impact marine waste streams, dredged sediments and mussel shells, characterized by high production volumes and complex matrices. This note reports preliminary results comparing sediment–cement mixtures with mixtures in which a portion of the cement is replaced by mussel shell powder produced via a thermo-mechanical treatment at low temperature. The dredged sediments were treated in their natural state to promote a sustainable approach. The methodology adopted does not appear to compromise the short-term mechanical performance of the mixtures, as evidenced by the compressive and oedometer test results presented in this study. Long-term durability will be assessed in subsequent phases of the project through dedicated monitoring and testing programmes. The results indicate that for both sediments, despite their significant differences in geotechnical properties, the proposed approach demonstrates comparable, if not superior, performance to previous studies on marine clays. Interestingly, at laboratory geotechnical scale, mixtures produced with the sandier and less plastic Barletta sediment exhibited the highest mechanical performance, despite identical water-to-additive ratios and treatment conditions applied to the more organic, fine, and plastic Bari sediment. Ongoing research focuses on the production of the first industrial prototypes of outdoor interlocking pavers made from sediment–mussel shell mixtures, both in powder and granulate forms, combined with binders. These prototypes will undergo mechanical testing, including indirect tensile tests and compressive strength tests (Fig. 11a-b), alongside monitoring for stability under atmospheric conditions. Future research directions aimed at further enhancing mixture properties include the incorporation of natural fibers from stranded *Posidonia oceanica* (Karimiazar 2026, Karimiazar et al. ref da SCOPUS IOP da aggiungere, Fig. 12a) to improve ductility, and the application of an acetic acid-based thermo-chemical treatment of mussel shells to produce a bio-additive (soft-calcite; Carcagni 2027 e ref ICC da aggiungere, Fig. 12b) with high sorption capacity (Murphy et al., 2020). The soft calcite additive is expected to reduce organic pollutants and heavy metals in sediments with higher contamination levels, further promoting the sustainability of this approach.

5 ACKNOWLEDGEMENTS

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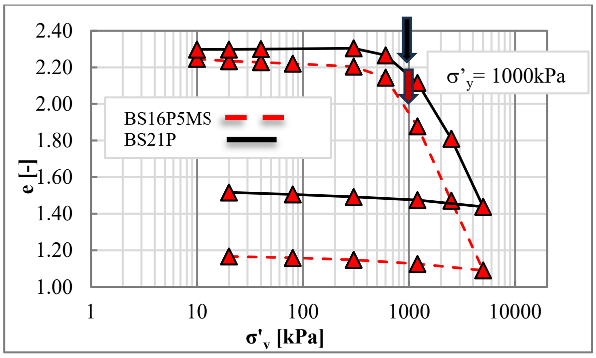

Figure 9: Oedometer test results using cement (BS21P) and cement and mussel shell powder (BS16P5MS) after 28 days of curing in seawater.

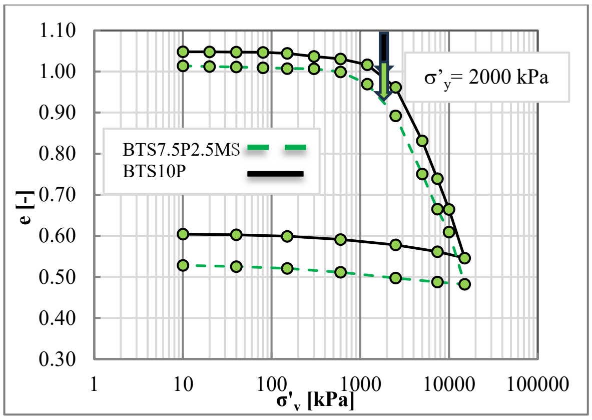

Figure 10: Oedometer test results using cement (BTS10P) and cement and mussel shell powder (BTS7.5P2.5MS) after 28 days of curing in seawater.

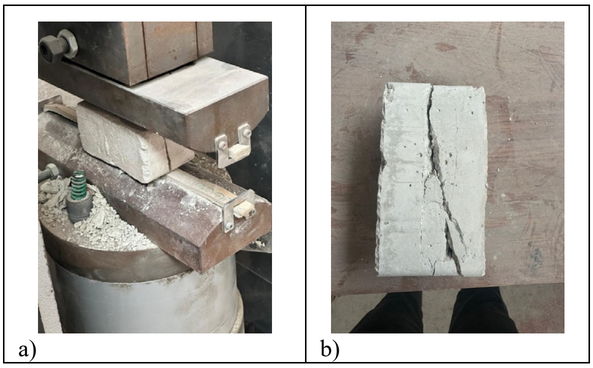

Figure 11. Outdoor paving blocks: a) Indirect tensile strength test; b) example of the first prototype (6x6x12 cm).

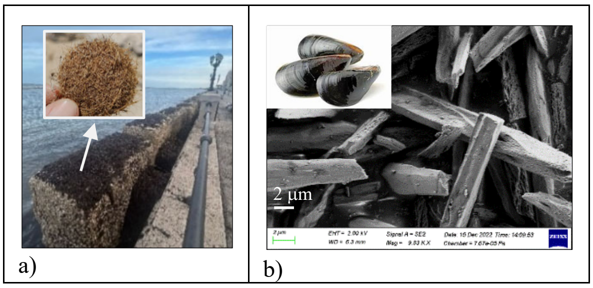

Figure 11. Materials used to enhance the chemo-mechanical performance of the mixtures: a) *Posidonia oceanica* fibers; b) SEM image of soft calcite, a biogenic absorbent produced via thermo-chemical treatment of mussel shells.

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