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Valorization of marine bio-waste in sustainable cementitious composites: Experimental performance and predictive optimization

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Abstract

The growing demand for climatic responsive construction materials increased the interest in valorising marine bio-waste as sustainable alternatives to conventional cement cubes. The study investigates the mechanical and physical performance of cement cubes incorporating calcium rich marine bio-waste as additives which includes shrimp shell, fish bone, lobster shell, oyster shell, and sea shell at varying percentages. Experimental evaluation was conducted to determine compressive strength, failure load, water absorption, dry density, and wet density of modified mixes in comparison with conventional control specimens. Linear and polynomial regressions are developed for each material category, and multivariable regression models were established to predict strength behaviour. The results demonstrated that strength response is material-dependent and non-linear, with shrimp shell and fish bone mixes exhibiting discernible optimum ranges, whereas lobster shell additions generally led to strength reduction at higher percentages and the optimum dosage is 4%. Multivariable regression incorporating physical parameters achieved up to 70% explanatory capability, establishing the significant influence of density and absorption on strength development. The findings confirm the feasibility of using selected marine bio-wastes as sustainable modifiers, highlight the necessity of material-specific optimization, and contribute predictive analytical tools supporting circular economy-based construction practices.

Keywords

Marine bio-waste; Calcium carbonate; Circular economy

1. INTRODUCTION

Sustainable development in the construction sector has become a global imperative due to escalating environmental concerns, depletion of natural resources, and the high carbon footprint associated with cement-based materials. Concrete, being the most widely used construction material, contributes significantly to greenhouse gas emissions and it is expected that the demand for concrete will rise in future (Tkachenko et al. 2023). In parallel, rapid growth of fisheries and marine food industries has resulted in the accumulation of large volumes of shell-based bio-waste, most of which is disposed in landfills or buried in seawater (Cheng et al. 2023). It takes more time to decompose causing odour, serious environmental and ecological problems (Popovic et al. 2023). Stacking and burying the oyster, shrimp and lobster shells change the composition, physical and chemical properties of soil, which significantly reduce the ability of soil to retain fertilizer and water, infect aquatic organisms, pollute soil and water, and then affect human health (Kumar and Hemalata 2020; Yang et al. 2022). Hence,

proper disposal of discarded shells has become a relatively urgent environmental issue in coastal areas (Lakhiar et al. 2024).

2. BACKGROUND RESEARCH (REVIEW OF LITERATURE)

Marine shells are primarily composed of 95 wt.% of calcium carbonate and 5 wt % organic compounds (Barthelat, and Rabiei 2011). Previous studies have reported the potential usage of shrimp shells (Jia et al. 2023; Priyanga et al. 2023; Zeyad et al 2026), fish bone (Avramenko et al. 2023), fish scale (Sulaiman et al. 2025), oyster shell (Kuo et al. 2013; Liao et al. 2022; Ruslan et al. 2022; Rux et al. 2025), sea shell (Bamigboye et al. 2021a,b; Bamigboye et al. 2022; Bellei et al. 2023; Kumar and Hemalata 2020; Owuamanam and Cree, 2020; Wang et al. 2019), in construction as filler material, admixtures, or partial replacements of cement and aggregates. The mechanical performance, durability response, and optimum levels vary widely depending on material type, physicochemical characteristics, and dosage. It is observed there is a lack of studies to address the structural and non-structural application of marine shell waste as an aggregate or binder in the composition of coating and laying mortars. Moreover, the existing literature relies predominantly on experimental comparisons (Gangabhavani et al. 2024; González et al. 2015; Koswaththa et al. 2025; Poloju et al. 2018) without incorporating predictive modelling tools that can establish reliable strength–property relationships or optimize replacement dosage for sustainable application. An attempt is made in this paper to valorise marine bio waste into value-added construction materials as controlled low strength material, a viable pathway toward achieving circular economy objectives while reducing environmental impact.

The marine bio-waste chosen in this study are shrimp shell, lobster shell, fish bone, oyster shell and sea shell and is added as additives with cement with different percentages. The study evaluates mechanical (compressive strength and failure load) and durability characteristics (water absorption, and density) of mortar cubes to assess the structural viability of the mixes with different dosages. In addition to conventional experimental analysis, polynomial and multivariable regression models are employed to characterize non-linear behaviour, quantify the influence of density and water absorption on strength development, and predict optimum dosage level of marine bio-waste for sustainable performance enhancement. The combination of experimental validation and predictive modelling represents the principal novelty of the research, offering a more efficient methodology for optimizing marine bio-waste utilization in sustainable concrete production.

3. MATERIALS AND METHODS

3.1 Materials

Ordinary Portland cement (OPC) 53 grade cement is used in this investigation. Initial and final setting time and fineness of cement are measured, conforming to ASTM C191 (2021) and ASTM C786-10(2016). Fine aggregates are collected from the natural dune sand of Jeddah-Makkah Road in Saudi Arabia. The particle size distribution of fine aggregate is obtained from a sample of 1375g through a set of sieves of size 4.75 mm, 2.36mm, 1.18mm, 0.6 mm, 0.3mm and 0.15mm.

Shrimp, oyster, lobster shell, fish bones and sea shells (Fig.1) are collected from the shore and water of red sea. The marine bio-waste was thoroughly washed to remove adhering impurities and a significant proportion of soluble salts. The cleaned materials were subsequently dried under sunlight and then oven-dried at 110°C for 24 h to eliminate residual moisture and improve material stability before grinding. It should be noted that oven drying at 110°C does not completely remove the organic constituents present in the marine bio-waste; rather, it primarily removes free and bound moisture while reducing surface contaminants. The dried marine bio waste is grinded with a blender, of size varies from 0.075 mm to 4mm (Fig. 2). For all the cubes the ratio of the cement to sand is 1: 1.5 and the water cement ratio is 0.25 and the all cubes are cured for 21 days and is mixing is done by hand mixing with proper care and the marine waste was added as additive with respect to weight of the cement.

3.2 Methods

Marine bio-waste (Shrimp, oyster, lobster shell, fish bones and sea shells) is added with cement as dry mix to cast mortar cubes from 0 % to 8% with respect to weight of cement. Increasing the dosage of marine bio waste reduces the hydration and adhesion which in turn causes significant reduction in interfacial bonding (Abirami and Sangeetha 2022; Singaravel 2024).

The compressive strength of the cubes of size 50 x 50x 50 mm is checked on 28th day with different dosage of marine bio-waste. Three specimens are casted for each dosage and average value is calculated. The durability of the cubes with and without marine bio-waste are determined from dry density and water absorption tests. Water absorption test is conducted as per ASTM C 1585-20 (2020).



Fig.1: Collection of Marine bio-waste



Fig. 2: Preparation of the marine bio-waste materials

4. RESULTS AND DISCUSSION

4.1 Mechanical and Durability Test Results

The mechanical and durability test results of different marine waste with different dosage is shown in table 1. Based on the materials, it is found that shrimp shell absorbs less water but the strength reduces significantly compared to conventional mortar cube due to weaker particle integration or poor bonding (Abbas and Kudukkan 2025). Cubes with shrimp shell exhibit high durability by absorbing less water but due to its poor compressive strength performance, its usage is limited for structural application.

Lobster shell and fish bones show high strength than conventional mix due to residual collagen and mineral content but show poor durability. The high-water absorption is due to porosity development or weaker matrix bonding (Eziefula et al. 2018), which compromise long-term durability. Cube with fish bone showed comparatively higher failure load values, particularly at 2%, but its normalized compressive strength did not exhibit consistent enhancement, and subsequent higher percentages resulted in poor mechanical performance.

Sea shell shows poor mechanical performance due to high organic residue interference during hydration and durability is high. Oyster shell shows best balance in strength, durability and structural reliability. Density results showed that mix with oyster shell-maintained values close to the conventional mix, indicating that the integration of oyster shell particles did not lead to detrimental porosity or excessive void formation. The stable density behaviour, combined with good strength retention, reinforces its suitability for structural or semi-structural applications.

Chitin is extracted from crustacean oyster shell waste and it has less molecular weight analysis (Mohan et al. 2021) and the same is observed in the test results. Also, the SEM analysis of the chitin shows the nanofiber and nanopore flake like structure (Koswaththa et al. 2025).

Marine bio waste especially shrimp shell, fish bone and oyster shell is suitable to use as controlled low strength cementitious materials (CLSM). The American Concrete Institute ACI 229 R-99 defines a CLSM as a self-compacting, flowable, durable and strong cementitious material mainly used to replace conventional back-filling soil and structural fillings.

Table 2 shows the strength, durability and optimum percentage of different Marine bio-waste Materials and it is found that oyster shell of 4% shows best performance in terms strength and durability.

From an engineering perspective, cube with oyster shell provides acceptable compressive strength, controlled water absorption, and stable density. This balance is critical for applications where durability performance and structural integrity are essential.

Table 1: Mechanical and durability test results

Marine bio-waste	Percentage added (%)	Normalized Failure Load of the cubes	Water Absorption (%)	Normalised Dry density	Normalized Wet density
Conventional	0	1	100%	1.00	1.00
Shrimp Shell	1	0.453	51%	0.99	1.00
Shrimp Shell	1.5	0.535	44%	0.97	0.99
Shrimp Shell	2	0.679	25%	1.01	1.06
Lobster Shell	2	1.048	96%	0.94	0.96
Lobster Shell	3	1.030	109%	0.99	1.00
Lobster Shell	4	1.011	109%	0.94	0.98
Lobster Shell	5	0.865	40%	0.96	0.99
Lobster Shell	8	0.824	55%	1.02	1.04
Fish bone	2	1.177	115%	0.99	1.00
Fish bone	3	0.938	119%	1.01	1.02
Fish bone	4	1.048	109%	0.98	1.00
Oyster Shell	4	1.112	46%	1.01	1.05
Oyster Shell	8	1.009	46%	1.02	1.06
Sea shell	2	0.577	33%	1.09	1.13
Sea shell	3	0.453	44%	1.07	1.09

Table 2: Comparative performance of marine bio-waste

Marine bio-waste	Strength	Durability	Optimum Percentage (%)
Shrimp Shell	Low	High	2
Lobster Shell	High	Low	4
Fish Bone	High	Low	2
Oyster Shell	High	High	4
Sea Shell	Low	High	2

Based on its performance consistency, oyster shell mix can be confidently considered for non-prestressed structural elements, general construction material, architectural components, and moderately loaded structural members. Additionally, the material's manageable absorption characteristics suggest suitability in environments where exposure to moisture is anticipated, provided conventional durability design measures are followed.

Oyster shells composed of calcium carbonate (CaCO_3), chemically which is similar to raw materials already used in conventional cement. Utilizing this naturally occurring CaCO_3 reduces dependency on virgin limestone mining, supports responsible material stewardship, and transforms a problematic waste into a useful product for construction industry. This aligns with UN Sustainable Development Goal (SDG) 12: Responsible Consumption and Production, and supports evolving green construction policies advocating waste valorisation, material circularity, and embodied-carbon reduction in the built environment.

4.2 Regression Analysis of Mechanical Properties

Fig. 3 indicates a clear variation in performance among the different marine-bio waste additives tested at various percentages. The highest measured response was observed for 4% lobster shell. The subsequent treatments—including fish bone, oyster shell, shrimp shell, and sea shell—show progressively lower values, reflecting a consistent decline in performance as one move across the series. This distribution is further emphasized by the cumulative trend line, which follows a typical Pareto pattern, where a small number of high-impact treatments account for the majority of the total effect. The cumulative curve approaches saturation toward the rightmost treatments, highlighting the diminishing returns associated with lower-performing additives. Overall, the graph underscores the predominance of lobster shell treatments in contributing to the measured outcome, while indicating that certain shell types and higher inclusion levels offer comparatively limited benefits. Overall, the graph demonstrates that lower percentage of lobster shell is the most influential; whereas shrimp shell and sea shell treatments contribute minimally.

From the analysis it is found that linear model is not adequate because the effect strongly depends on type of shell, not only on percentage. It is recommended to do polynomial regression of degree 2. From the quadratic model it is found that the load carrying capacity is increases up to 3 to 4% and then it declines slowly towards 8%. From the results it is suggested that moderate addition of marine bio-waste from 2 to 4 % tend to yield high strength whereas very high and very low percentage shows less strength. But again, variation is strongly influenced by type of marine -bio waste material added with the cement.

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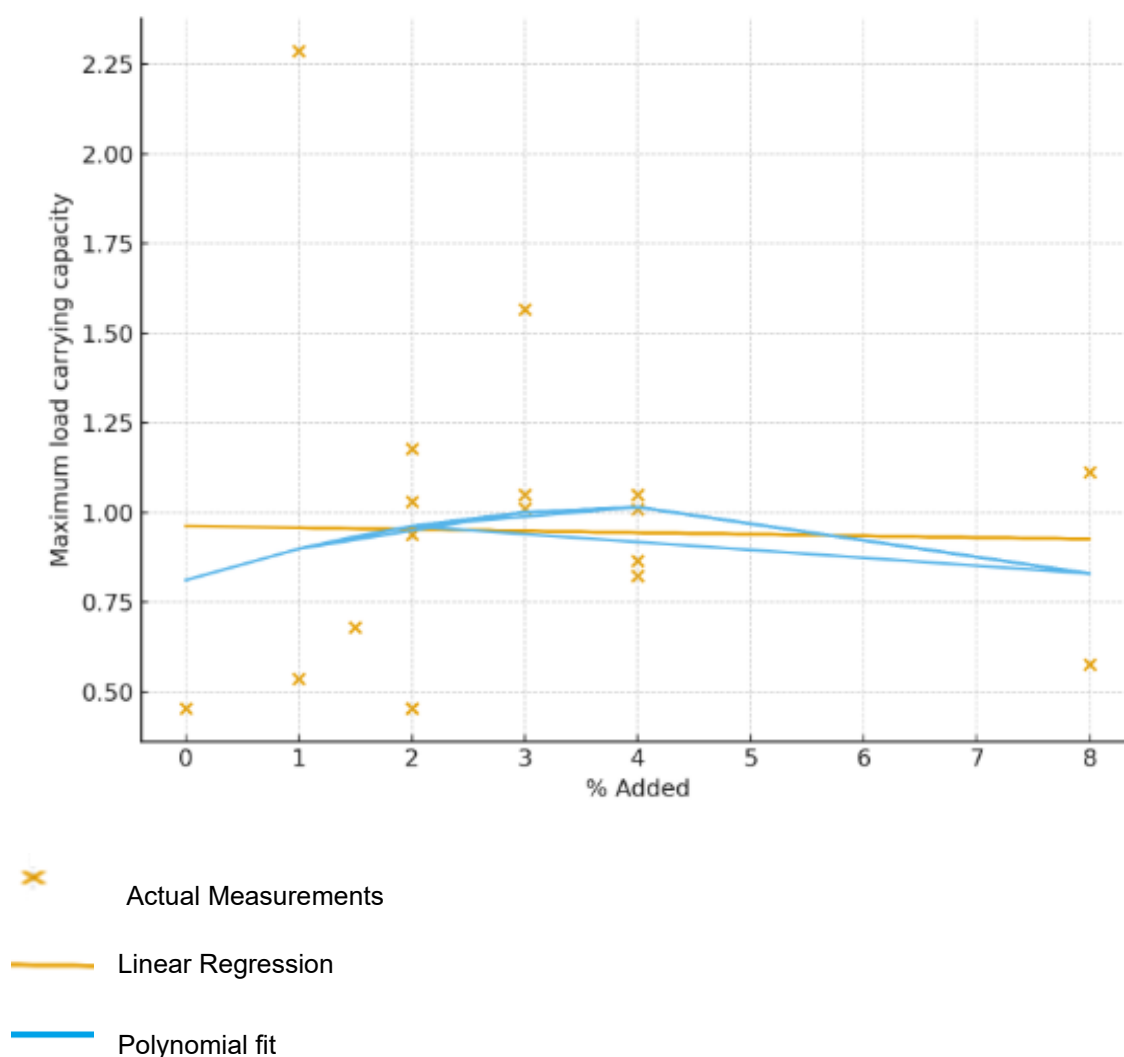


Fig. 3: Optimal percentage of materials added with the normalized maximum load carrying capacity

4.3 Material-Wise Regression Models and Prediction of Optimum Dosage

A preliminary pooled linear regression using percentage replacement as sole predictor yielded a negligible explanatory capability ($R^2 = 0.003$), confirming that material type is a critical determinant and the effect cannot be generalized across additives. A categorical multiple-regression model including material dummies improved explanatory capability substantially ($R^2 = 0.90$); so material-wise regressions provide clearer engineering interpretation and are therefore emphasized.

Linear, polynomial and quadratic regression analyses were performed for each marine bio-waste to avoid masking material-specific effects. Quadratic regression models were adopted to account for potential non-linear behaviour of strength with respect to percentage of marine waste (P). Only material groups with ≥ 3 data points were modelled statistically; groups with two data points are described but not fitted due to insufficient degrees of freedom.

The predicted compressive strength and failure load based on linear and polynomial regression analysis for marine bio-waste is shown in Table 3 and Table 4.

Table 3: Predicted compressive strength for different marine bio-waste material

Marine Bio-waste Material	Optimum percentage	Linear regression Analysis	Polynomial regression analysis
Shrimp Shell	1.26%	$f_c = 0.239 + 0.126 P$ $R^2 = 0.73$	$f_c = 0.794 - 0.673P + 0.266P^2$ $R^2 = 1$
Lobster Shell	0.96%	$f_c = 0.878 - 0.0297 P$ $R^2 = 0.70$	$f_c = 0.951 - 0.0644P + 0.00332P^2$ $R^2 = 0.72$
Fish bone	3.18%	Insufficient data	$f_c = 2.130 - 0.876P + 0.138P^2$ $R^2 = 1$
Sea shell		Insufficient data	

f_c = Compressive strength P is the dosage of the marine-bio waste

R^2 is close to 1, and it shows that regression fits the data extremely well. From the vertex $-\frac{b}{2a}$, the optimum percentage of Shrimp shell to be added is 1.26% and the predicted normalized compressive strength is 0.37 as shown in Fig. 4 (a). The optimum percentage of Lobster shell is found to be 0.96 % and the predicted compressive strength is 0.83 as shown in Fig. 4(b). The regression models are intended to illustrate overall trends rather than to establish precise optimum dosages because of their limited goodness-of-fit (low R^2 values). The optimum percentage of fish bone is found to be 3.18 % and the predicted compressive strength is 0.73 as shown in Fig. 4 (c). Regression fitting is statistically unreliable for the results obtained for sea shell and thereby description discussion is concluded that the capacity increase in the percentage range of 2 to 3.

Table 4: Predicted Failure load for different marine bio-waste material

Marine Bio-waste	Linear regression analysis	Polynomial regression analysis
Shrimp Shell	$F = 0.217 + 0.226 P$ $R^2 = 0.98$	$F = 0.475 - 0.145P + 0.124P^2$ $R^2 = 1$
Lobster Shell	$F = 1.115 - 0.0378 P$ $R^2 = 0.70$	$F = 1.208 - 0.0819P + 0.00422P^2$ $R^2 = 0.72$
Fish shell	Insufficient data	$F = 2.704 - 1.113P + 0.175P^2$ $R^2 = 1$
Sea shell	Insufficient data	

F = Failure load P is the dosage of the marine-bio waste

4.4 Multivariable Regression Analysis

Multivariable regression analysis is carried out to understand the combined effects of percentage of marine bio-waste, physical and durability characteristics (density and water absorption) as dependent variable to find the compressive strength,

$$f_c = -0.671 + 0.0325P + 0.00403W + 7.79\rho_d - 6.65\rho_w$$

$$R^2 = 0.70$$

Where

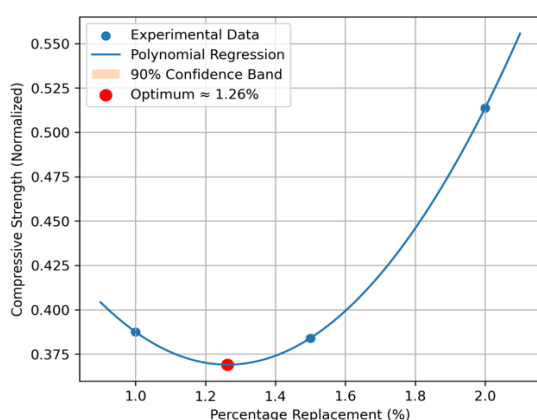
P = percentage of marine bio-waste (%)

W = water absorption (%)

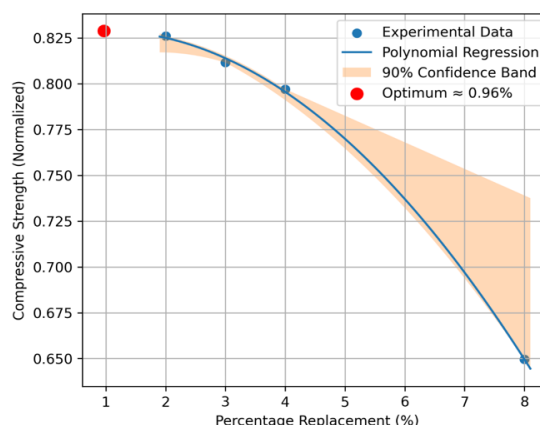
ρ_d = dry density (g/cm³)

ρ_w = wet density (g/cm³)

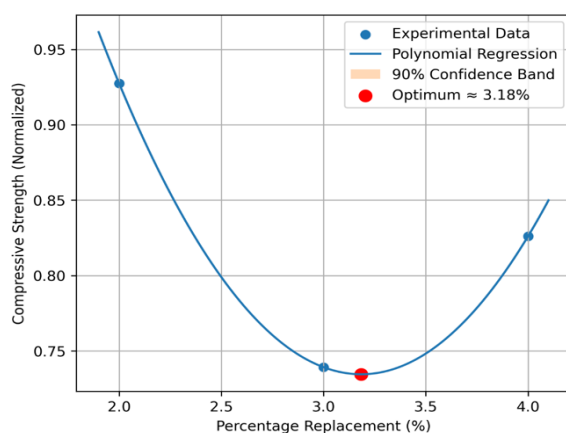
f_c = Compressive strength



a) Shrimp shell



b) Lobster Shell



c) Fish bone

Fig. 4: Regression Analysis for individual marine bio-waste

Water absorption exhibits a positive coefficient, indicating that mixtures with moderate absorption (likely due

to micropore refinement or matrix densification) may still sustain reasonable strength. Dry density is positively associated with strength, consistent with a denser microstructure improving load resistance. Wet density shows a negative coefficient, implying that higher retained moisture correlates with weaker matrix bonding or internal void saturation effects. The relatively high R^2 confirms that absorption and density parameters significantly govern compressive strength alongside replacement percentage.

Variance Inflation Factor (VIF) analysis indicated strong interdependence between dry and wet densities ($VIF > 7-9$). Removing one variable slightly reduced explanatory capability but improved compressive strength.

$$f_c = -2.64 + 0.0118P + 0.00709W + 2.82\rho_d$$

$$(R^2 = 0.60)$$

Thus, both density parameters together improve prediction accuracy, but they should be interpreted cautiously due to correlation.

6. CONCLUSIONS

Based on integrated analysis of strength, failure load capacity, water absorption behaviour, and density performance, Oyster Shell at 4% replacement is identified as the optimal marine bio-waste additive with cement in this study. This composition demonstrates the most favourable balance between mechanical efficiency and durability assurance, making it a strong additive for sustainable structural and semi-structural applications in future research and practice. From the regression analysis it is found that the strength behaviour is non-linear, and optimal additive content exists for shrimp, lobster and fish shell rather than a monotonic trend. Physical and durability indices (density and absorption) are strong predictive indicators, explaining up to 70% of strength variability. The regression analysis is presented as a trend-analysis tool to illustrate the relationship between marine bio-waste content and the measured properties. The small number of dosage levels restricts the statistical robustness and predictive applicability of the regression models.

From sustainability perspective, the successful integration of marine bio-waste contributes to circular economy objectives by diverting waste from landfills and reducing reliance on virgin mineral fillers. It is recommended to include comprehensive characterization of the marine bio-waste through chemical (XRF/XRD), mineralogical, and microstructural (SEM/EDS) analyses to quantify calcium carbonate content, residual organic matter, particle morphology, and the interfacial transition zone with the cement matrix as future study.

The integration of marine bio-waste into cement directly contributes to decarbonization targets and circular economy objectives. Although the replacement level investigated in this study is modest (4%), even small material substitutions can yield meaningful environmental benefits when scaled to industry practice. Additionally, diversion of marine bio waste from landfills prevents biological decomposition and related environmental

burdens, while eliminating the need for costly sterilization and disposal programs commonly implemented in coastal cities.

Beyond structural considerations, the practical benefits extend to waste management and environmental policy implementation. Valorisation of marine bio-waste reduces landfill pressure, mitigates disposal challenges, and supports circular economy objectives within coastal regions and fishery-dependent communities. Therefore, the proposed mix not only demonstrates technical feasibility but also aligns with global sustainability frameworks and emerging green-construction regulations.

This study did not include detailed characterization of the marine bio-waste, such as particle-size distribution, chemical/mineralogical composition, and specific gravity, owing to the limited quantity of processed materials available. The investigation primarily focused on evaluating the influence of marine bio-waste additions on the mechanical properties of cement cubes and developing predictive regression models. Future studies should incorporate comprehensive material characterization to better correlate the properties of marine bio-waste with concrete performance.

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10. BACKGROUND INFORMATION FOR RECORD (NOT TO BE PRINTED)

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