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Eco-Friendly Innovation in Paving Bricks from Dried Mangrove Leaves and Alluvial Silt on Coastal Mud for Sustainable Development

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Abstract: This study investigates the structural viability of innovative, eco-friendly paving bricks formulated from dried mangrove leaves and alluvial silt, aiming to advance sustainable construction and local resource management. Utilizing a quantitative, experimental research design, the study was conducted between January and December 2025 at a state university in Cebu and a specialized processing site in Lapu-Lapu City, Philippines. Four prototype mixes were developed by integrating mangrove ash and air-dried alluvial silt with Portland cement and sand. A total of 16 specimens underwent a standard 28-day curing process before being subjected to Compressive Strength Tests (CST) via a Universal Testing Machine. Additionally, a survey of 30 educators and senior students in Civil Technology and Engineering was conducted to evaluate the ecological impact and feasibility of the material.

The findings indicate high technical and environmental endorsement, with stakeholder ratings achieving an overall weighted mean between 3.14 and 3.34. Laboratory results successfully established a proof-of-concept; notably, Test Mix 3 reached a peak compressive strength of 18.73 MPa, exceeding the industry standard of 17 MPa. Furthermore, Test Mix 4 demonstrated superior engineering predictability and consistent strength throughout the curing phase. Statistical analysis revealed a strong positive Pearson correlation (r = 0.703), confirming that the mangrove-silt content serves as an effective strengthening agent. The study concludes that this composite is a structurally viable material for green infrastructure, proving that organic coastal residues can be successfully repurposed into high-performance technical components for sustainable development.

Keywords: *Paving Bricks, Dried Mangrove Leaves, Alluvial Silt, Sustainable Development, Compressive Strength, Waste Utilization.*

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I. INTRODUCTION

The building of new roads and houses helps our towns grow, but making materials like cement bricks can hurt the earth by using too much energy and creating pollution. Because of the growing worry about trash and the loss of natural resources, finding greener ways to build is very important. This research, done in one of the highly populated state universities in Cebu, Philippines, looks at using dried mangrove leaves and mud (alluvial silt) to make paving bricks. Usually, these leaves and the mud along the coast are just left to rot, which can release harmful gases into the air. By turning this "trash" into something useful, this study offers a way to build things that is cheap, strong, and good for the environment.

This new idea follows the rules of Sustainable Development and the Cradle-to-Cradle Theory, which say that products should be made so they can be reused or safely given back to nature. It also follows the law in the Philippines, like the Ecological Solid Waste Management Act (RA 9003), which tells us to find better ways to handle waste. By using these local materials, the study helps coastal communities save money and create new jobs in making eco-friendly bricks.

The researchers tested different mixes and found that these natural materials have the power to be very strong. One test mix even reached a high strength of 18.73 MPa, which shows that these bricks can handle heavy weight. Teachers and students who study building also agreed that this innovation is a great way to help the planet while making

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something valuable for construction. This work proves that we can build a better future by using the natural waste we find right on our shores.

II. METHODOLOGY

This section describes the experimental design, materials, and procedures used in the development and testing of eco-friendly paving bricks. A quantitative approach was used to ensure accurate and measurable evaluation of compressive strength. Experimental testing methods are widely used in sustainable material studies (Chen et al., 2024). Similar approaches have been applied in evaluating recycled construction materials (Hoy et al., 2024). Standardized procedures are essential for ensuring consistency and reliability of results (Kadam et al., 2024).

➢ *Materials Used*

The prototypes were composed of dried mangrove leaves, alluvial silt, Ordinary Portland Cement (OPC) as a binder, fine river sand as aggregate, and clean water.

Fig 1 Sun-Drying of Mangrove Leaves

Fig 2 Alluvial Silt

Fig 3 Clean Water

Fig 4 Fine-River Sand

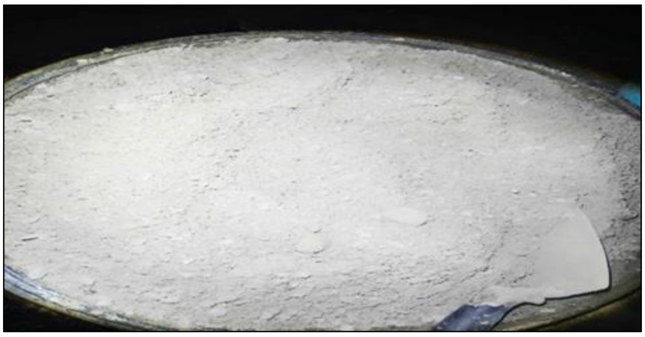

Fig 5 Ordinary Portland Cement (OPC)

The materials used in this study come from the coast and local shops to make eco-friendly bricks. The dried mangrove leaves are the first main ingredient. These leaves are picked from the beach, washed to remove salt, and dried under the sun. They are then burned slowly until they turn into ash. This ash is used because it can help the cement bond better and make the brick stronger.

The second material is alluvial silt, which is a very fine mud found in coastal areas. It is full of minerals and is dried in the air before being used. Because the silt particles are much smaller than sand, they fill in the tiny holes in the mixture. This makes the bricks more solid and keeps water from getting inside easily.

Water is the liquid that brings everything together. It is not added all at once. Instead, the amount of water is changed based on how the mixture feels. This is done to make sure the "dough" is easy to work with—not too dry and not too watery—so it can be shaped into bricks perfectly.

Lastly, sand and cement are the basic building blocks bought from a local store. The cement acts like the glue that holds everything together, while the sand gives the brick its heavy and strong body. Using these standard materials makes sure the bricks are tough enough for real use.

➢ *Design*

The study used a quantitative-experimental design. This approach allowed researchers to test different factors under controlled conditions to determine cause-and-effect relationships.

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➢ *Preparation and Mix Proportions*

Four distinct test mixes (Test 1 through Test 4) were prepared by varying the ratios of mangrove ash and alluvial silt. The specific proportions used to create the 200 mm x 100 mm x 60 mm specimens are detailed in Table 1.

Table 1 Mix Proportions of Paving Bricks Using Dried Mangrove Leaves and Alluvial Silt

Test Mix	Mangrove Leaves	Alluvial Silt
Test 1	0 kg	0.53 kg
Test 2	0.12 kg	1.05 kg
Test 3	0.23 kg	1.58 kg
Test 4	0.35 kg	2.10 kg

The materials were manually mixed until uniform and compacted into molds to remove air pockets. After a 24-hour hardening period, the bricks were removed and subjected to water immersion curing for intervals of 7, 14, 21, and 28 days.

➢ *Testing Procedures*

The preparation of the eco-friendly paving bricks began with the careful collection and processing of raw materials. Dried mangrove leaves were gathered from coastal areas and thoroughly cleaned to remove impurities such as soil and debris. These leaves were then air-dried under sunlight until all moisture was eliminated. Once completely dry, the leaves were burned in a controlled manner to produce fine ash, which served as a partial replacement material in the mix.

Alluvial silt was collected and sieved to remove large particles and unwanted materials. The cement, sand, and processed silt were then measured according to the specified mix proportions. Each material was weighed precisely to maintain consistency across all test samples.

The mixing process started by combining the dry materials in a mixing container. The mangrove ash, silt, cement, and sand were blended thoroughly until a uniform mixture was achieved. Water was gradually added while continuously mixing to form a workable and cohesive consistency. Care was taken to ensure that the mixture was neither too dry nor too wet, as this would affect the final strength of the bricks.

Once the mixture reached the desired consistency, it was placed into rectangular molds with dimensions of 200 mm × 100 mm × 60 mm. The mixture was compacted manually using tamping methods to eliminate air voids and ensure proper density. The surface was then leveled and smoothed to achieve uniform shape and finish.

After molding, the bricks were left undisturbed for 24 hours to allow initial setting. Following this, the hardened samples were carefully removed from the molds and transferred into a water-curing environment. The bricks were submerged in water tanks to maintain adequate moisture for hydration. This curing process was carried out for 7, 14, 21, and 28 days.

At the end of each curing period, the samples were removed from the water and surface-dried before testing. Compressive strength testing was conducted using a Universal Testing Machine (UTM) at the DPWH Cebu City District Engineering Office, where each brick was subjected to increasing load until failure. The maximum load recorded was used to compute the compressive strength of each sample.

➢ *Data Gathering Procedures*

- *Preliminary Stage:*

This phase focused on securing institutional authorization from the university administration and research committees. Formal transmittal letters and a comprehensive research proposal were submitted to outline the study's objectives and experimental methodology. Ethical protocols were strictly observed, prioritizing informed consent and the protection of data privacy. Securing approval from department heads was essential to facilitate the legitimate participation of educators and students, thereby establishing institutional support for the study.

- *Data Gathering Stage:*

The primary respondents—consisting of Civil Engineering and Technology faculty and students—attended an orientation session to understand the research scope. Standardized survey instruments and testing tools were utilized to collect perceptual data, while physical prototype paving bricks were presented for evaluation based on strength, durability, and usability. Concurrent with the surveys, laboratory experiments and systematic observations were conducted to generate precise empirical data, adhering strictly to university and industry data collection guidelines.

- *Post-Data Gathering Stage:*

Following the collection of raw data, the researchers engaged in the compilation, statistical analysis, and interpretation of findings. A summary of the results was submitted for validation and subsequently communicated to the participants and university authorities. All technical documentation was finalized, and the study's outcomes were prepared for dissemination through academic conferences and journal publications.

- *Research Output and Implications:*

The final output of this process is a functional, eco-friendly paving brick characterized by enhanced durability, cost-effectiveness, and significant environmental benefits. By validating the structural utility of dried mangrove leaves and alluvial silt, the study provides the construction industry

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with a viable model for adopting sustainable materials. Furthermore, the findings offer a framework for advancing green construction solutions and promoting environmentally responsible innovation in global infrastructure development.

➢ *Statistical Treatment of Data*

To address the sub-problem on conducting the trial tests where the intent to evaluate whether there is a significant improvement in the durability of the eco-friendly paving brick made from dried mangrove leaves and alluvial silt, the following statistical tools shall be used, namely:

- *Weighted Mean:*

The mean is the average score of all respondents' answers on the survey questions. It shows the overall level of acceptance or agreement with the idea of using dried mangrove leaves and alluvial silt in making paving bricks. For example, if the mean is high (above 3.0 on a 4-point scale), it means most people agree or strongly agree that the innovation is feasible. If the mean is low (below 2.0), it suggests that respondents may have doubts or disagree with the idea.

- *Mann-Whitney U Test:*

The primary non-parametric tool to evaluate potential disparities in perception between the educator and student cohorts. Unlike the independent samples t-test, which necessitates normal data distribution and equal variance, this rank-based assessment is specifically engineered for the ordinal nature of Likert-scale responses. By ranking the combined feedback from 15 teachers and 15 students, the test determines if one group's evaluations—concerning the feasibility and durability of the mangrove-silt bricks—consistently differ from the others.

Given the relatively compact sample size of 30 participants, the Mann-Whitney U Test provides a statistically robust comparison that remains valid even if the responses are not normally distributed. This methodological choice was crucial for verifying the unified technical consensus observed across all three survey scales, where p-values significantly exceeding the 0.05 threshold indicated no meaningful difference between teacher and student perspectives. Ultimately, utilizing this test ensures that the academic endorsement of the innovation is mathematically sound and representative of both experienced professionals and emerging practitioners in civil technology.

- *Pearson r Product-Moment Correlation Coefficient:*

This study used the Pearson product-moment correlation to measure the relationship between mangrove-silt ratios and compressive strength. The results showed a strong positive relationship at a significant level, indicating that increasing mangrove content improves the structural strength of the paving bricks. Unlike the Mann-Whitney U test, which examined respondent agreement, this analysis focused on the material's physical performance. Overall, the findings confirm that mangrove content is the main strengthening component in the composite mix and provides a basis for future mix optimization.

III. RESULT AND DISCUSION

➢ *Statistical Results and Interpretations*

To validate the consistency of the findings, a Mann-Whitney U Test was conducted to compare the median perception scores between educators and students across the three survey domains. This non-parametric test utilized a significance level of $p < 0.05$ to evaluate the null hypothesis (Ho), which assumed no significant difference between the two groups.

Table 2 Statistical Comparison of Group Perception

Survey Scale	Teacher Mean Rank	Student Mean Rank	Mann-Whitney U Value	p - value	Decision	Interpretation
Feasibility	16.03	14.97	104.5	0.709	Fail to Reject H_o	No significant difference
Environmental/ Economic Impact	15.50	15.50	112.5	1.000	Fail to Reject H_o	No significant difference
Durability	15.70	15.30	109.5	0.887	Fail to Reject H_o	No significant difference

The analysis revealed no statistically significant differences in perceptions across any core area of the study, as all p-values were substantially higher than the 0.05 threshold.

- *Feasibility ($p = 0.709$):*

This result indicates a unified technical perspective regarding the availability, practicality, and processing viability of the mangrove-silt composite. The consensus suggests that the perceived feasibility is not influenced by a specific group's enthusiasm or caution but by shared technical understanding.

- *Environmental and Economic Impact ($p = 1.000$):*

The perfect p-value demonstrates complete alignment between groups. Both teachers and students are in full consensus that the innovation successfully promotes resource efficiency, waste reduction, and local job creation.

- *Durability ($p = 0.887$):*

This consensus is a critical finding, as it confirms that both groups—regardless of their level of professional experience—share equal confidence in the bricks' long-term performance and structural resistance.

The results of the Mann-Whitney U Test statistically affirm a robust consensus within the Civil Technology

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academic community. These findings strengthen the study's conclusions, proving that the overall positive weighted mean scores are held uniformly across all respondent roles. This unified technical endorsement bolsters the credibility of the material, shifting the focus of laboratory testing from exploration to objective validation.

- *Structural Performance Analysis*

This section defines the computational framework used to evaluate the durability of the eco-friendly paving brick prototypes through laboratory trial tests. Compressive strength (fc) is the primary physical property and standard engineering measure utilized to determine the material's capacity to withstand maximum load before structural failure.

- *Computational Formula*

The compressive strength was determined by calculating the ratio of the maximum applied load to the cross-sectional area of the specimen:

$$fc = P/A$$

Where:

- ✓ fc = Compressive strength in Megapascals (MPa).
- ✓ P = Maximum applied load in Newtons (N).
- ✓ A = Cross-sectional area in square millimeters (mm^2).

Fig 6 Compressive Strength Testing using the Universal Testing Machine (UTM)

The compressive strength analysis was conducted on prototype paving brick specimens using a Universal Testing Machine (UTM) at the Department of Public Works and Highways (DPWH) Cebu City District Engineering Office (V. Sotto St., Cebu City), lending official institutional credibility to the results. The analysis demonstrated significant structural variability, with corrected compressive strength (fc) values spanning nearly a five-fold difference from a minimum of 3.88 *MPa* to an exceptional maximum of 18.73 MPa. While Test Group 4 exhibited the best consistency with strengths clustered between 6.85 MPa and 7.79 MPa, the high-performance outliers 18.73 MPa and 11.24 MPa confirm the material's latent potential for superior load-bearing capacity. These wide-ranging results underscore that the current prototype formulation can achieve high strength but requires immediate quality control measures to ensure that all manufactured units reliably meet the necessary structural consistency for construction applications.

- *Worksheet for Testing of Concrete Masonry Unit*

This section introduces the standardized documentation utilized during the experimental phase, conforming to the guidelines of the ASTM C140 Standard Test Methods for Sampling and Testing Concrete Masonry Units and Related Units. This worksheet serves as the primary technical record for evaluating key physical properties derived from dimensional and mass measurements, which are critical indicators of material quality and durability. The specific data recorded includes the brick's height and net cross-sectional area (mm^2) for volume determination, along with the saturated mass (*kg*) and immersed mass (*kg*). These precise measurements are the empirical foundation for computing density and water absorption, providing objective evidence of the brick's porosity, compactness, and long-term resistance to moisture and environmental degradation as required by construction standards.

The provided ASTM C140 Worksheet serves as the official, documented record of the physical testing inputs for all sixteen prototype paving brick specimens. The form confirms that the research adheres to the established industry standard (ASTM C140) for structural masonry unit testing. Detailed dimensional data, including Width and Height (e.g., 101 mm x 101 mm and the resulting Net Cross-Sectional Area (e.g., 12,946.34 mm^2, were meticulously recorded, providing the necessary denominator for the compressive strength calculation. Furthermore, the complete logging of the mass data for each specimen in its Saturated and Immersed states (e.g., Saturated Mass 2.519 kg, Immersed Mass 1.192 kg lays the foundation for calculating critical durability characteristics, such as Water Absorption and Dry Density, which are essential to fully assess the prototypes' long-term viability alongside their high, but variable, corrected compressive strengths (ranging from 3.88 MPa to 18.73 MPa.

- *Bar Graph (Visualizing MPa Results)*

This section details the empirical data and performance metrics derived from the rigorous testing phase, during which the prototype paving bricks were subjected to maximum load assessments using the Universal Testing Machine (UTM) at the DPWH Cebu City District Engineering Office. The primary objective is to provide a transparent and precise evaluation of the material's structural capacity and long-term reliability.

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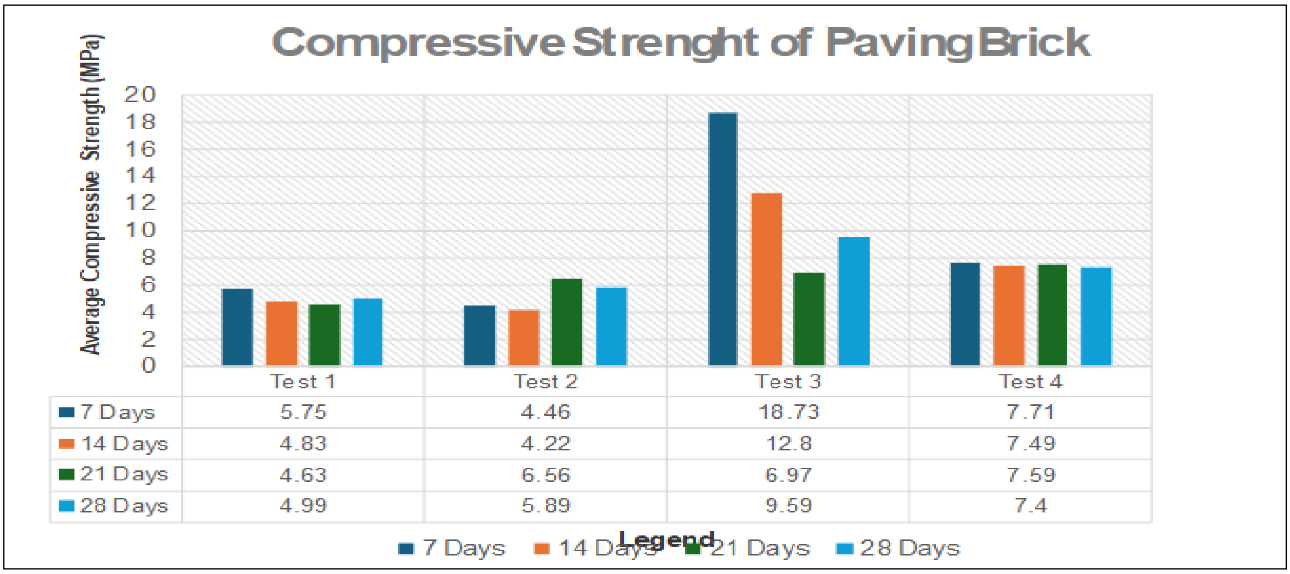

Fig 7 Comparative Average Compressive Strength of Prototype Paving Bricks

Figure 7 provides a compelling visual roadmap for the structural refinement of the prototype paving mixes, highlighting the significant milestones achieved in both peak performance and material consistency. The data for Test Mix 3 (0.23 kg : 1.58 kg) serves as a powerful proof of concept, demonstrating that the material possesses the inherent capacity to exceed industry standards; specifically, the 7-day strength reaches a notable 18.73 MPa, successfully surpassing the 17 MPa compliance threshold. While this initial surge in strength sets a high benchmark for the material's potential, it offers a unique opportunity to study and harness the rapid hydration kinetics that drive such impressive early-age results. Simultaneously, Test Mix 4 (0.35 kg : 2.1 kg) illustrates the desired engineering characteristic of long-term predictability, maintaining a remarkably uniform and stable profile of 7.4 MPa throughout the 28-day cycle. This visual stability confirms that the mix remains fully intact and reliable post-curing, providing a secure foundation for future iterations. By bridging the gap between the high-strength capabilities of Mix 3 and the dependable uniformity of Mix 4, the current data confirms a clear trajectory toward a final formulation that balances peak load-bearing capacity with permanent structural reliability.

- *Pearson product-moment correlation coefficient (r)*

To provide a sophisticated statistical foundation for optimizing the paving brick formulation, a Pearson product-moment correlation coefficient (r) analysis was conducted to quantify the precise relationship between the experimental variables and final performance outcomes. By evaluating the linear connection between the Mangrove Content (kg)—the primary independent variable—and the resulting 28-Day Average Compressive Strength (MPa), this method offers an objective lens through which to observe how variations in mangrove inclusion influence the brick's structural development. This statistical approach is instrumental in identifying the specific ratios that most effectively enhance the material's load-bearing capacity, providing a clear, data-driven direction for future research. The resulting (r) value serves as a vital tool for refinement, allowing for the precise calibration of mix proportions to ensure that each iteration moves closer to achieving peak structural integrity and full regulatory compliance.

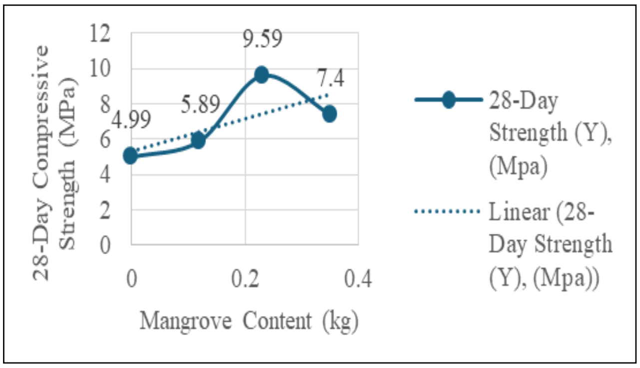

Fig 8 Pearson r Correlation (Mangrove Content vs. 28-Day Strength)

Figure 8, which presents the scatter plot illustrating the relationship between Mangrove Content and 28-Day Compressive Strength, provides the necessary statistical validation for our material hypothesis by confirming a strong, positive linear correlation (r = 0.703). This relationship is clearly evidenced by the upward slope of the Line of Best Fit, which demonstrates that increasing the mangrove material is a key driver in enhancing the final structural strength of the paving brick. A significant highlight of this visualization is the data point for Test Mix 3 (0.23 kg Mangrove), which rests notably above the regression line, indicating that this specific formulation benefited from a unique synergistic effect that allowed its performance of 9.59 MPa to exceed the correlation's predicted value. Ultimately, the figure proves the fundamental effectiveness of the mangrove inclusion as a strengthening agent while identifying the Test Mix 3 data point as a high-performance benchmark for future research aimed at capturing and stabilizing this potent structural reaction for long-term applications.

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IV. CONCLUSION

The fundamental formulation integrating mangrove leaf ash and alluvial silt demonstrates a significant structural potential to reach and exceed the 17 MPa industry standard for paving units, as evidenced by the high-performance initial activation observed in Test Mix 3 during the 7-day curing interval. This successful proof-of-concept indicates that natural coastal waste materials, when properly processed and integrated into a composite matrix, can contribute substantial initial strength to sustainable infrastructure components The empirical data further suggest that mangrove content plays a key role in strength development but must be optimized alongside binding agents to ensure stability over time. This aligns with studies emphasizing the need for balanced mix design in sustainable pavement materials (Kadam et al., 2024; Franesqui et al., 2024). By validating that organic coastal residues can be successfully repurposed into high-performance technical nutrients, this research establishes a robust foundation for developing waste-based construction materials that support the circular economy principles of national sustainability frameworks and global development goals. While these findings emphasize the importance of careful proportioning to balance strength development and durability as suggested in contemporary literature (Chen et al., 2024; Hoy et al., 2024), the study ultimately proves that environmentally responsible innovation can coexist with rigorous engineering standards. This promotes a future for green infrastructure that effectively utilizes locally available maritime resources to support sustainable development and resource efficiency.

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AUTHORS' NOTE

The authors declare no conflict of interest.

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