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Comparison between two models of 3D printed artificial coral

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KEYWORDS

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ABSTRACT

This study provides a comparative analysis of two models of 3D-printed artificial coral reefs, focusing on key design elements essential for effective reef construction. It begins with an overview of natural coral ecosystems and discusses the importance of artificial reefs in marine conservation. The paper then establishes fundamental design criteria, including ecological functionality, structural integrity, biocompatibility, and environmental resilience. Two distinct reef models were created, prototyped, and subjected to laboratory-scale assembly and performance evaluations. The assessment parameters included printing techniques, assembly, and the potential to support marine life. The comparative results reveal unique advantages and limitations in each model's capacity to replicate natural reef structures, promote biodiversity, and endure harsh marine conditions. The study concludes with practical recommendations for selecting and optimizing artificial reef designs tailored to specific environmental contexts. Overall, the findings underscore the promising potential of 3D printing technology in fostering sustainable and resilient artificial reefs for marine ecosystem restoration and protection.

1. Introduction

1.1. Introduction to coral reefs

A coral reef is a remarkable marine ecosystem created through the close relationship of coral polyps - living organisms that belong to the phylum Cnidaria and the class Anthozoa. These polyps can secrete calcium carbonate, allowing them to build a complex skeletal framework that gradually forms the extensive structures known as coral reefs over time. Unlike ordinary rocks or sediments, coral reefs are often referred to as "living architectures," as they consist not only of the remains of deceased organisms but also provide habitats for countless other marine species, including algae, seaweed, fish, crustaceans, and mollusks. Coral reefs primarily flourish in tropical marine environments where conditions are optimal, characterized by abundant sunlight, stable water temperatures (ranging from 22 to 29 °C), shallow depths, and suitable salinity levels [1].

Figure 1. Natural coral reef (left) and the degradation (right).

In recent years, the degradation of natural coral reefs has intensified globally, particularly within tropical marine regions, including Vietnam. The primary factors contributing to this decline are the significant impacts of climate change, such as ocean warming leading to widespread coral bleaching, destructive fishing practices, and marine pollution from both industrial and domestic sources. The loss of coral reef areas and their quality has directly jeopardized coastal ecosystems, destroying habitats for numerous aquatic species, accelerating coastal erosion, and posing a serious threat to the livelihoods of local fishing communities. In response to these challenges, the research and development of artificial coral reefs have emerged as a critical solution for restoring biodiversity and stabilizing the marine environment [2], [3]. Modern 3D concrete printing technology, in particular, offers remarkable potential by enabling flexible design, precise simulation of complex natural coral morphologies, material optimization, and reduced construction times, thus improving the effectiveness of marine restoration efforts [4], [5], [6]. Consequently, the research, design, and fabrication of 3D-printed concrete artificial reefs hold significant scientific and practical importance. They contribute to the conservation of the biosphere, the restoration of marine habitats, and the sustainable development of the marine economy in Hai Phong City and across Vietnam.

Artificial coral reefs are man-made structures designed to simulate natural habitats for corals and marine life, typically installed on the seabed. They are crucial in restoring degraded marine ecosystems affected by climate change, pollution, and overfishing. Beyond providing habitat for marine organisms, artificial reefs also act as natural breakwaters, reducing wave energy, preventing coastal erosion, and stabilizing the seabed. Encouraging coral recruitment and

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enhancing local biodiversity contributes significantly to marine conservation and sustainable resource management. Globally, artificial reef projects have been actively implemented [5], [7]. Florida has developed large-scale programs in the United States using concrete blocks, decommissioned ships, and steel structures to create artificial reefs for marine research and tourism, notably the USS Oriskany, the world’s largest artificial reef. In Japan, artificial reefs help restore commercial fish and seaweed habitats, supporting local fisheries. Australia also experiments with artificial reefs to assist coral resettlement near the Great Barrier Reef. Southeast Asian countries such as Thailand, Indonesia, and Malaysia have deployed artificial reefs to protect coastlines and encourage coral restoration. In Vietnam, artificial reef initiatives have been introduced in key ecological and tourist areas. Besides biodiversity conservation, artificial reefs in Vietnam also help mitigate wave impacts, support coastal fisheries, and promote dive tourism, offering a sustainable pathway for marine resource management amid ongoing environmental challenges.

The author examines two distinct models based on established criteria for artificial coral reef design. The process begins with prototype fabrication in the laboratory, where each design undergoes thorough evaluation for structural integrity and biocompatibility. Following successful assessments, both models are assembled and installed on-site to evaluate their performance within a dynamic marine environment. A comparative analysis showcases each design's strengths and weaknesses, focusing on factors such as stability, effectiveness in promoting marine life, ease of installation, and resilience to environmental challenges. From this analysis, tailored recommendations arise to guide future projects in selecting the most appropriate design based on specific conditions and ecological objectives. These artificial reefs present a promising opportunity to enhance biodiversity, stabilize coastlines, and support sustainable fisheries within our marine ecosystems.

1.2. Key Design Principles for Artificial Coral Reef

Designing artificial coral reefs involves a combination of structural engineering, material science, and marine ecology [9], [7], [10], [11], [12]. The objective is to replicate marine habitats, safeguard coastlines, stabilize seabeds, and enhance biodiversity. A successful design must balance technical specifications, biological adaptability, and long-term durability. Key criteria include:

- Biocompatibility: Materials must be safe, non-toxic, and compatible with coral and marine organism colonization. They should exhibit chemical stability, maintain a neutral pH (between 8.1 and 8.4), and be devoid of heavy metals. Recommended materials include marine-grade concrete, ceramics, biocomposites, and natural stone, all resistant to saltwater corrosion and wear. The surfaces should feature appropriate roughness, grooves, and micro-cracks to facilitate larval attachment.
- Durability in Marine Environments: Designs must be robust enough to endure temperature variations (ranging from 20 °C to 35 °C), salinity, pressure, and currents. Structures should also resist cracking and damage from marine organisms such as oysters and barnacles.
- Structural Stability and Load Capacity: Artificial reefs should be designed to withstand dynamic forces generated by waves, currents, and debris. Taking into account the type of seabed (sand, gravel, silt, or rock), it is crucial to prevent settling or overturning. Optimized geometry and mass distribution are vital for enhancing stability under challenging marine conditions.
- 3D Habitat Diversity: Effective artificial reef designs should include a variety of cavities and shelters to support an array of marine species. Ensuring adequate water circulation within the structure is critical to prevent sediment buildup and maintain necessary nutrient and oxygen levels. Features like ridges, slopes, cracks, and small caves should be incorporated to replicate the structural complexity of natural reef habitats, thereby fostering the attraction and settlement of diverse marine life.

Designing artificial reefs requires a careful blend of construction engineering, structural mechanics, material science, and marine ecology. Adhering to these criteria ensures that artificial reefs restore ecosystems, protect coastlines, and promote marine biodiversity.

1.3. Geometry and Structural Selection

In the realm of artificial reef design, the interplay of geometry and structure serves not only mechanical functions but also pivotal ecological purposes, significantly shaping the success of habitat restoration. To truly flourish, an artificial reef must emulate the intricate, three-dimensional (3D) formations of natural coral reefs while harmonizing with its environment's unique geographic, hydrological, climatic, and biological elements.

A fundamental principle in the design of artificial reefs is to replicate the topography and ecology of natural coral reefs, ensuring seamless integration into existing marine ecosystems. This involves the incorporation of diverse voids and cavities within the structure, which provide crucial shelter, feeding, and breeding grounds for a wide range of marine organisms, including microorganisms, corals, mollusks, crustaceans, and fish. Additionally, the complexity of reef structures aids in dissipating current energy, thereby reducing seabed erosion and stabilizing sediment. This, in turn, fosters the creation of ideal microhabitats for coral larvae and juvenile organisms. Moreover, the design must prioritize environmental protection by buffering against strong wave impacts and retaining fine sediments and nutrients essential for coral attachment and growth, ultimately supporting long-term ecological sustainability.

Artificial reefs' geometry and surface characteristics are vital in influencing biological behaviors and promoting habitat sustainability. Complex structures, such as multi-layered, polyhedral, hollow-branch, and interlocked modular forms, increase surface area and create diverse microenvironments that support enhanced biodiversity. These intricate designs foster various marine species by augmenting habitat complexity. Furthermore, micro-textured surfaces with fine cracks mimic the natural surfaces of coral reefs, encouraging the attachment of coral larvae, algae, and invertebrates while improving friction to withstand strong currents. Strategically placed water ventilation holes, informed by hydrodynamic analysis, ensure optimal water flow through the reef. This facilitates the transport of nutrients and oxygen, the removal of waste, and the stabilization of the surrounding ecosystem, all essential for maintaining the health and growth of reef organisms.

Selecting the geometry and structure of coral reefs is a delicate dance between engineering ingenuity and ecological wisdom. Designs that truly succeed must evoke the beauty of natural three-dimensional spaces, thoughtfully integrating voids, textured surfaces, and dynamic water flow systems. This harmonious approach creates a visually stunning environment and fosters vibrant and resilient marine life communities, ensuring that our oceans thrive in their full splendor.

2. Materials and methods

2.1. Materials and Mix Proportions

For this research, the binder component was developed using ordinary Portland cement (OPC) from Chiffon PC40 and fly ash (FA) sourced from the Haiphong thermal power plant. This combination was selected due to the favorable results of researchers with cement-based materials. In this study, both commercially available natural sand and crushed sand were employed. Polypropylene (PP) fibers were incorporated into the concrete mix to help reduce shrinkage during printing and curing. The key properties of the PP fibers are listed in Table 1.

Table 1. Properties of PP fiber.

Tensile strength	500 MPa
Modulus	6000 MPa
Diameter	35 +/-5 μm
Length	12 mm
Specific density	0.910 kg/l

ViscoCrete®-3000-20 M, a superplasticizer, was used to adjust the workability of the fresh concrete. Figure 2 presents the materials used for mixing concrete in this research.

The materials selected for this research - Ordinary Portland Cement (OPC), fly ash (FA), natural and crushed sand, and polypropylene (PP) fibers - are well-suited for the Biocompatibility criteria in artificial coral reef construction. OPC and FA provide good chemical stability and maintain a neutral pH (8.1–8.4), ideal for colonization of marine life. While fly ash may contain trace heavy metals, its use is suitable as long as it is adequately sourced, ensuring minimal environmental risk. PP fibers are non-toxic and chemically inert, contributing to the mix without affecting pH or introducing harmful substances. The combination of natural and crushed sand creates a rough surface texture supporting larval attachment. At the same time, PP fibers reduce cracking, enhancing the concrete's resistance to wear and saltwater corrosion. Together, these materials offer durability, stability, and surface characteristics that promote marine organism colonization, making them suitable for artificial reef applications, provided that the fly ash is carefully sourced to avoid excessive heavy metal content. The mix proportion of ingredients is introduced in Table 2.

Cement | Fly ash | Natural sand | Crushed sand | PP fiber | Superplasticizer

Figure 2. Materials used for mixing concrete.

Table 2. Mix proportion.

Cement	Fly Ash	Water	Natural sand	Crushed sand	PP Fiber (%)	SP (%)
0.75	0.25	0.32	0.5	0.5	0.25	0.4

(Note: Binder = Cement and Fly Ash; values in Table are ratios of each ingredient to binder)

2.2. Design models

Based on the design criteria analyzed in Section 1, the research team focused on proposing an artificial coral reef structure centered around key factors, while considering the feasibility of 3D concrete printing technology:

Ecological functionality requirements encompass intricate structural features and essential elements that support marine life. The design should closely emulate the characteristics of natural reefs, and 3D concrete printing provides the flexibility to create complex geometries that mirror the intricacy of natural coral reefs while ensuring environmental functionality.

Structural design requirements include load-bearing capacity, stability in the face of wave and current forces, and compatibility with the marine environment. 3D printing with concrete enables precise control over material properties and structural integrity, ensuring the reef can endure dynamic marine conditions. Additionally, this approach guarantees that the materials used are non-toxic and conducive to colonizing marine life.

The selection of complex geometries, such as hollow cavities, crevices, and small shelters, is essential for accurately replicating the features of natural coral reefs and providing habitats for marine organisms. 3D concrete printing is a highly effective method for achieving these intricate designs, enabling the creation of detailed and diverse structures that enhance biodiversity and offer crucial microhabitats for various marine species. Additionally, the printing process can be optimized for cost-effectiveness and efficiency in producing these complex designs, ensuring practicality for large-scale implementation.

These considerations ensure that the proposed design for the artificial coral reef structure meets ecological and structural requirements and remains practical for construction using 3D concrete printing technology. As a result, the authors propose that each block in the structural design consists of three well-defined segments: the base, the middle, and the top components. Each segment is expertly designed to incorporate six large perforations, a central small core hole, and eight gear-like features, as depicted in. The diameters of the base, middle, and top segments of the Model 1 and 2 are precisely specified to be 900 mm, 700 mm, and 500 mm, as illustrated in Figure 3 and Figure 4, respectively. This intentional decrease in diameter from the base to the top is intended to improve the stability and load distribution of the single block structure. Such a tapered design ensures a lower center of gravity, enhancing structural integrity in the face of various environmental loads [13].

Both reef models feature identical overall perimeter dimensions. The primary distinction lies in the internal connections between the inner and outer rings of the coral structure. Specifically, the designs differ in the configuration of joints, perforations, and protruding legs, which are essential for modular assembly. As highlighted in the analysis section, these variations are anticipated to affect structural behavior. Both models are constructed using the same 3D-printable concrete material to ensure uniformity in material performance.

The Table 3 provides a comparative analysis of two design models based on several key features. It highlights the differences in printing difficulty, structural strength, material consumption, assembly stability, and visual appearance. Additionally, it includes a description of the construction requirements for each model, offering insights into the practical considerations for their implementation in real-world applications.

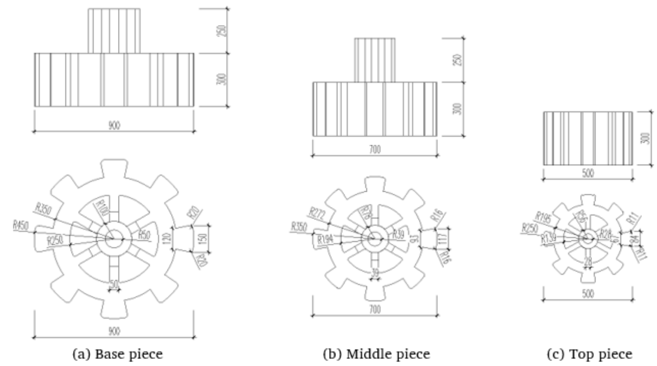

Figure 3. Details of Model 1.

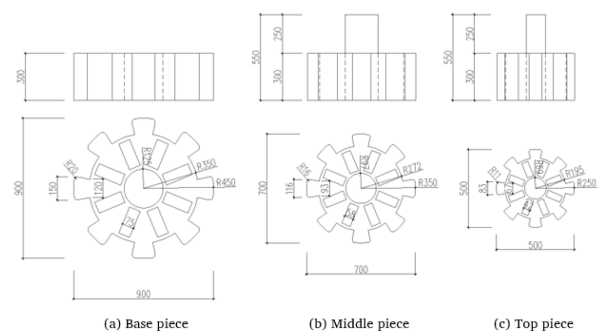

Figure 4. Details of Model 2.

The proposed design of the artificial coral reef features three distinct segments: base, middle, and top. This structure meets established criteria for artificial reefs, incorporating perforations and gear-like structures that enhance complexity and modularity. The tapered shape, decreasing in diameter from base to top, improves stability and load distribution, providing a lower center of gravity essential for resilience against environmental forces like currents and waves. This intricate design supports ecological needs by increasing surface area and creating diverse microenvironments, fostering biodiversity through varied shelters and feeding grounds for marine organisms. The micro-textured surfaces replicate natural coral, encouraging the attachment of coral larvae, algae, and invertebrates. Water ventilation holes ensure proper nutrient and oxygen exchange flow, waste removal, and ecosystem stabilization. Thus, the design enhances both the physical stability of the reef and its biological and ecological sustainability.

Table 3. Comparison of Model 1 and Model 2.

Feature	Model 1	Model 2
Printing Difficulty	High; requires an additional bottom layer to connect the inner and outer rings; sand formwork is used to create internal voids for future block connections.	Low, no additional bottom layer or special formwork required
Structural Strength	High; capable of withstanding significant loads	Lower; less capable of bearing heavy loads
Material Consumption	Higher material usage, resulting in increased weight	Lower material usage, contributing to reduced weight
Assembly Stability	High; components interlock securely, providing enhanced stability	Lower; components may require additional support during assembly
Visual Appearance	Massive and solid, conveying robustness	Slimmer and lighter, offering a more delicate appearance

2.3. Printing task

The process begins with creating a 3D CAD model of the object, which is saved in ".STL" format. Next, the Simplify3D software [14] slices the model into layers and exports it as a ".Gcode" file. This file contains the instructions for producing the cross-sectional layers, which are then sent to the 3D printer. Finally, the 3D concrete printers, operated using Mach3 software [15], print the components. Simplify3D was utilized to slice the 3D coral reef models into layers and generate the necessary G-code for the 3D concrete printer. Key slicing parameters, such as layer height, infill pattern, and print speed, were carefully optimized to achieve a balance between printing time and structural integrity. Mach3 was employed to control the printer's motion system, ensuring precise execution of the toolpath during fabrication. These software tools were chosen for their compatibility with custom-built 3D concrete printers and their established reliability in prior studies involving complex geometries, including our previous work.The printer fabricates the object by applying each layer through selective material placement. This process is illustrated in Figure 5.

Adjust the operating parameters of the 3D concrete printer—including printing speed, dimensional accuracy, and extrusion pressure (Figure 6), and selecting appropriate printhead types - to align with the design's technical specifications. The printer must be capable of fabricating highly complex geometries with fine structural details while maintaining high precision and consistency throughout the printing process. Special attention should be given to optimizing the printing path and layer deposition to ensure the integrity and stability of intricate features such as hollow cavities, crevices, and small shelters.

After meticulously completing the printing process and strictly adhering to the established protocols, the concrete was blended according to the precise mix design specified in the table. The printed products of the two coral models are elegantly displayed in Figure 7 and Figure 8. This striking visual representation highlights each model's unique characteristics and intricate structural features. It facilitates a meaningful comparative analysis of their design and performance within the dynamic marine environment. Each sample reflects the innovative parameters established in the research, showcasing the significant potential of 3D-printed artificial coral reefs to contribute to marine conservation efforts.

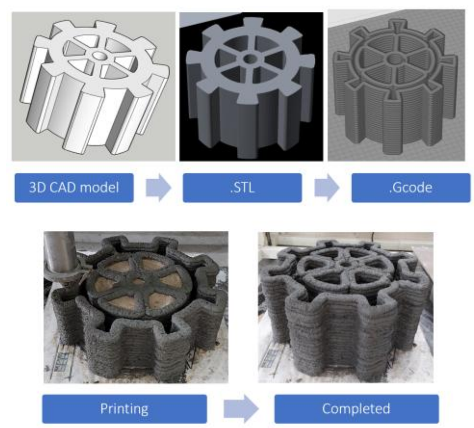

Figure 5. Printing process.

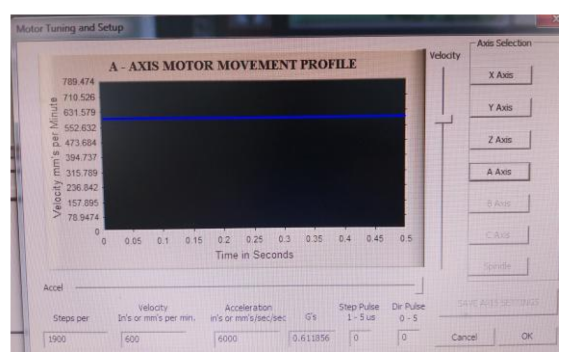

Figure 6. Extruder speed setup.

(a) Top piece (b) Base and Middle pieces

Figure 7. Printed Model 1.

(a) Top and middle pieces (b) Base pieces

Figure 8. Printed Model 2.

3. Results and discussion

3.1. Printing techniques

In practical construction, for Model 1, including an additional bottom layer is essential to establish a secure connection between the outer and inner rings of the printed block. To connect the outer and inner, click "Edit Process Settings," then in the tab "Layer," five or more bottom solid layers are defined, as illustrated in Figure 9.

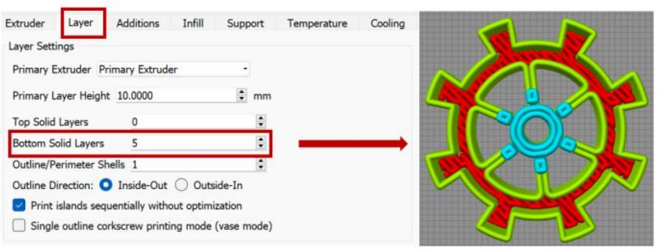

Figure 9. The technical command inside Simplify 3D.

This bottom layer is designed to create internal voids, which facilitate the interconnection of the individual blocks during the subsequent assembly phase. A sand formwork technique is employed to achieve this, as shown in Figure 10. The sand formwork serves a dual purpose: it accurately shapes the necessary voids within the bottom layer and contributes to preserving structural integrity by maintaining the block's geometric stability throughout the printing and curing processes. This approach ensures the final structure meets the required assembly and load-bearing criteria while minimizing potential distortions during fabrication.

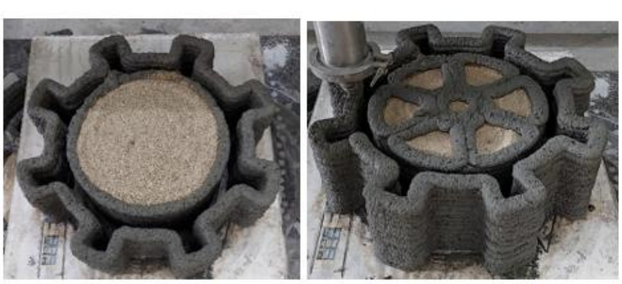

Figure 10. The technical command inside Simplify 3D.

3.2. Assembly techniques

According to the assembly process as shown in Figure 9. The three printed pieces were combined into one block. The solution utilizes an interlocking detail, as illustrated in Figure 8. Specifically, the recessed section of the middle component is fitted into the raised section of the base component with an insertion depth of 150 mm, as shown in the bottom view of the figure. Similarly, the top component is connected to the middle component using the exact interlocking mechanism. The complete assembly process for a single block following the second solution is presented in Figure 12 and Figure 13.

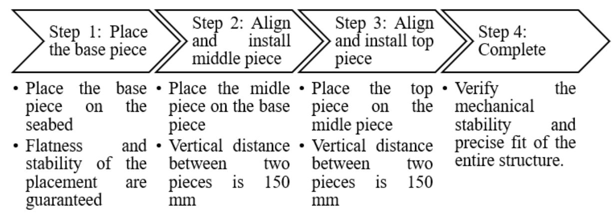

Figure 11. Assembly process.

Figure 12. Printed artificial coral - Model 1.

Figure 13. Printed artificial coral - Model 2.

Table 4. Comparative analysis of the two assembly methods.

Feature	Model 1: Slot-in via Raised Ridges	Model 2: Pegs into Pre-formed Holes
Assembly precision requirements	Moderate: Tapered ridges can assist in guiding parts together; minor printing deviations are still tolerable.	High: Pegs must align exactly with holes; even slight deviations can complicate assembly.
Installation speed	Fast: Components slot together quickly without much adjustment; highly efficient for field operations.	Slower: Pegs must be carefully aligned and inserted into holes; more time-consuming per unit.
Self-alignment capability during assembly	Good: Tapered ridges naturally guide the components into position during placement.	Moderate: Manual adjustment required to align pegs with holes; less self-guiding capability.
Operational stability	Good: Ridge engagement and self-weight ensure reasonable stability under calm marine conditions.	Good: Mechanical interlock between pegs and holes improves structural stability under dynamic loads.
Resistance to lateral/dynamic forces	Moderate: Primarily relies on weight and surface friction; strong waves could cause slight displacement.	Moderate: Mechanical interlocking resists lateral movement effectively, ideal for strong waves and current environments.
Assembly risk	Low: Misalignment can be easily corrected by repositioning; unlikely to cause structural damage.	High: Misalignment may cause pegs to break or jam; requires careful handling and precise assembly.

Table 4 presents a comparative analysis of the two assembly methods - Model 1 (Slot-in via Raised Ridges) and Model 2 (Pegs into Pre-formed Holes). Key features such as assembly precision, installation speed, self-alignment capability, operational stability, resistance to lateral and dynamic forces, and assembly risk are evaluated. The comparison highlights each model's relative advantages and limitations in field assembly and long-term performance under marine conditions.

Given the comparison of the two models, Model 1 (Slot-in via Raised Ridges) is recommended for environments with calmer waters or situations where speed and ease of assembly are critical. This model’s ability to facilitate faster, more forgiving assembly with lower risks makes it more suitable for large-scale operations or where assembly speed is a priority. On the other hand, Model 2 (Pegs into Pre-formed Holes) is better suited for areas exposed to strong dynamic forces, such as offshore locations with significant wave action. The interlocking feature provides superior stability and resistance to lateral forces, making it ideal for harsher marine environments where structural integrity under dynamic conditions is paramount.

4. Conclusions

This study compares two models of 3D-printed artificial coral reefs, focusing on critical aspects of coral and artificial reef design. It begins with an overview of coral ecosystems and highlights the significance of artificial reefs in marine conservation. The paper then outlines fundamental criteria for designing artificial reefs, which include ecological functionality, structural integrity, biocompatibility, and environmental resilience.

Two distinct design models were proposed, prototypes developed, and laboratory-scale assembly and testing followed. The performance of these models was assessed based on several key parameters, such as load-bearing capacity, stability under dynamic environmental forces, ease of assembly, and suitability for supporting marine life. A detailed comparison of the two models identified the strengths and weaknesses of each design, particularly in their ability to emulate natural reef characteristics, enhance biodiversity, and endure harsh marine conditions.

Ultimately, the study provides valuable insights into the practical application of 3D-printed artificial coral reefs and offers recommendations for selecting the most effective model based on specific environmental and operational conditions. The findings advocate for the use of 3D printing technology in developing sustainable and efficient artificial reefs, which have the potential to significantly contribute to the restoration and protection of marine ecosystems.

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Declaration of competing interest

The author declares that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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