Pham and Huang
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3D printed artificial coral reefs: design and manufacture

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Abstract

Applying 3D concrete printing (3DCP) technology to design and manufacturing can create a diverse configuration of the marine landscape. However, this combination of 3D technology and artificial coral products is still in the initial stage of research and application. Therefore, this study introduces a novel design shape model, bridging theory and experimental models. Two innovative design models have been presented, and one has been manufactured and assembled based on the optimal assembling process. The paper aims to propose a design shape model for artificial coral reefs that employs innovative 3D concrete printing technology to create rough surfaces with openings and cavities similar to those found in natural rocks. The proposed design shape for artificial coral reefs, successfully trialed in this research, can be used as a reference model. The procedure for essential works, including drawing, printing, assembling, and some techniques, is helpful for understanding and implementing the works presented in the study. The application of 3D concrete printing technology to an artificial reef fulfills an identified need and plays a crucial role in marine ecosystem restoration and protecting endangered habitats, thereby making a significant social impact while promoting sustainable development in construction. This paper fulfills an identified need to apply 3D concrete printing technology to manufacturing artificial coral reefs.

Keywords Artificial coral reefs, 3D concrete printing technology, Design shape models, Manufacturing process, Marine ecosystem

摘要

将3D混凝土打印技术应用于海洋景观的设计和制造中，可以极大提升海洋景观部品的设计自由度，然而，现阶段3D技术与人工珊瑚产品的结合仍处于研究和应用的初始阶段。因此，本研究结合新型设计形状模型，桥连了理论与实验模型。提出两种设计模型，其中一种基于最优组装工艺进行了制造和组装。本文旨在提出一种人工珊瑚礁的设计形状模型，该模型采用创新的3D混凝土打印技术制造而成，制备的人工珊瑚礁表面粗糙，孔洞和空腔与天然岩石相似。选取成功的人工珊瑚礁的形状可作参考模型，基础工作包括绘图，打印，组装及相关技术等，本研究工作将推动对人工珊瑚的理解和相关实践。将3D混凝土打印技术应用于人工珊瑚礁制造，可满足现实需求，为修复海洋生态系统和保护濒危物种栖息地起到至关重要的作用，在促进建筑业的可持续发展的同时，也产生了重大的社会价值。

关键词 人工珊瑚礁，混凝土3D技术，设计形状模型，制造工艺，海洋生态系统

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1 Introduction

Coral reefs are vibrant underwater ecosystems composed of colonies of reef-building corals, predominantly stony corals. These reefs offer habitats for diverse marine life, including sponges, oysters, clams, crabs, sea stars, sea urchins, and numerous fish species. They are ecologically connected to adjacent seagrass beds, mangroves, and mudflat communities. Coral reefs are highly valued not only for their stunning beauty but also for their crucial role in marine life activity. They serve as a vibrant ecosystem that supports a wide array of aquatic species.

Additionally, coral reefs provide essential ecosystem services, including nutrition for local communities, financial security through fisheries and tourism, and protection from natural disasters like storm surges. Their biological diversity makes them some of the most valuable ecosystems on the Earth, highlighting the importance of their conservation and protection. Coral reefs face significant threats from climate change, declining water quality, overfishing, and pollution. As a result, their populations are declining drastically. In response, artificial reefs have been developed to mimic the functions of natural coral reefs. These underwater structures can provide similar benefits, offering habitats for marine life while being less susceptible to the threats that impact natural reefs. By implementing artificial reefs, we can help maintain the ecological functions that coral reefs provide to the surrounding marine environments. Artificial reefs promote ocean biodiversity and protect shorelines from erosion and storm surges by dissipating wave energy. They enhance local fish populations and support algae growth. Additionally, they can obstruct ship movements, prevent trawling, and improve surfing conditions. Artificial coral reefs play a crucial role in boosting local fish populations and creating optimal conditions for algae growth.

Artificial reefs can be made from car tires, old vehicles, and scrap metal to create a suitable environment for fish and marine life, such as crabs, octopuses, and eels. Concrete blocks are preferred for reef projects because they are easier to handle and enhance plant and invertebrate growth due to their calcium content. They are also readily available, creating ideal habitats for fish to live, breed, and find protection. A new development technique has recently been applied to construction areas: 3D concrete printing (3DCP) technology. This technology enables the creation of complex habitats but is still under development. Companies are now designing more advanced reefs with superior materials to support marine life better, as shown in Fig. 1 [1]. Using sustainable materials like ceramic [2] or low-carbon concrete made from recycled materials enhances the benefits of coral reefs [3,

Fig. 1 Advancing 3D printed coral reef structures

4]. 3D printing technology enables the creation of complex shapes and designs, increasing habitat diversity and species richness. The size and shape of the reefs can be optimized for specific ecosystems. Once printed, the concrete reefs are deployed in the ocean, attracting marine organisms and forming new ecosystems.

Applying 3D concrete printing technology to design and manufacture can create a diverse configuration of the marine landscape. However, this combination of 3D technology and artificial coral products is still in the initial stage of research and application. Previous research revealed the design details and manufacturing process were often unveiled. To focus on the application, the authors are devoted to exposing as many details as possible, from the design to the construction of the proposed models.

Additive manufacturing, or 3D printing, has captivated researchers worldwide for decades. Its remarkable ability to turn concepts into real-world objects has also captured the imagination of engineers, architects, and investors. As the construction industry increasingly embraces this groundbreaking technology, we are witnessing a shift from merely creating quick prototypes to producing entire structures, revolutionizing how we build and design our environments. Since 2014, many iconic buildings and bridges have been constructed onsite using 3D printing technology [5–9]. The process involves four key steps: (1) creating a 3D CAD model, (2) exporting it to an STL file, (3) slicing it into a G-code file, and (4) printing with the right material mix. This ability to turn designs into physical objects has garnered attention from engineers, architects, and investors. As the construction industry adopts this technology, its applications are expanding from rapid prototyping to the entire production of final structures.

The eco-friendly benefits of 3D printing highlight how this technology contributes to a more sustainable future. Firstly, this method minimizes waste, using materials only where needed. The precision of 3D printing sustainability significantly reduces excess materials, promoting more efficient use of resources. Secondly, the eco-friendly benefits of 3D printing are known for its energy efficiency. 3D printing uses less energy since it directly constructs objects from digital models compared to traditional manufacturing, which often demands high energy consumption for cutting, drilling, and milling. The energy savings contribute to the overall sustainability of this technology, making 3D printing eco-friendly and a preferable choice for environmentally conscious manufacturers. Thirdly, a critical aspect of sustainable 3D printing is using eco-friendly materials, including recycled and reused materials. Finally, 3D printing can also lower the carbon footprint of manufacturing thanks to the ability to produce goods locally and on demand. 3D printing sustainability helps decrease the need for transportation and storage, significantly contributing to greenhouse gas emissions. In conclusion, 3D printing often requires less material than traditional manufacturing methods, reducing waste and energy consumption. This efficiency further contributes to a lower carbon footprint. By adopting 3D printing, industries can streamline production processes and enhance their commitment to environmental stewardship, making it a vital tool in the fight against climate change and reducing transportation emissions and resource usage, which positions 3D printing as a key player in moving toward more sustainable manufacturing practices.

2 Design of coral reefs

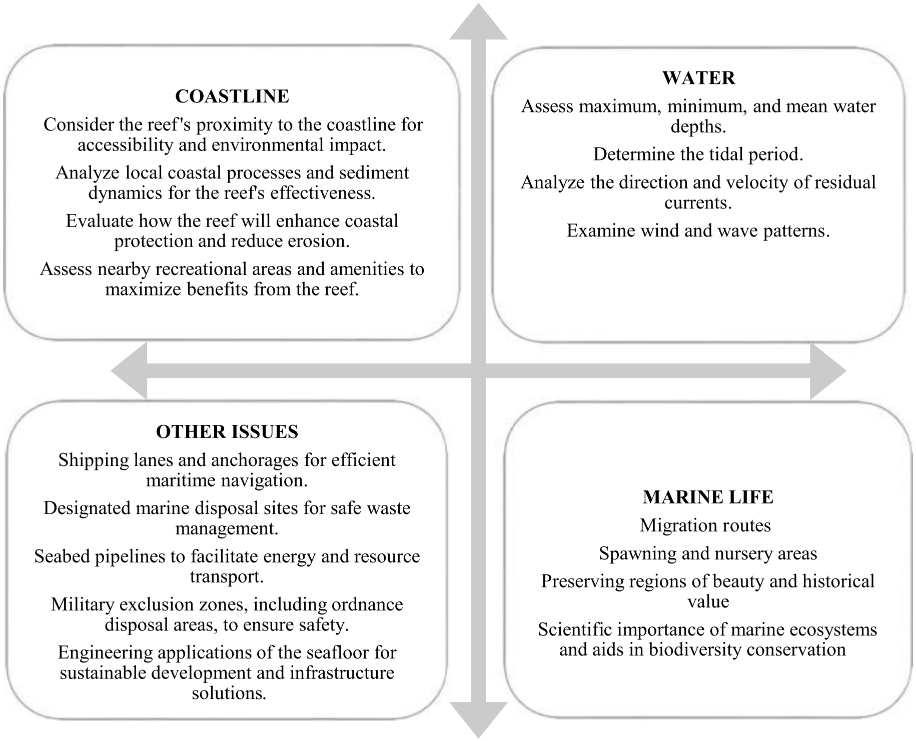
2.1 Design considerations

Firstly, the location of a proposed artificial reef must be carefully evaluated by considering several key aspects, as shown in Fig. 2 [10].

Secondly, the configuration, forms, and size of the artificial reef are crucial considerations. Research indicates that different species often show distinct preferences for specific designs. Factors such as the characteristics of the units (blocks or modules), their dimensions, size, mass, spatial heterogeneity, primary group of units, arrangement, and the distances between blocks all play significant roles in the overall design. Designs should be tailored to specific objectives and target species. Complex structures are essential, as greater complexity directly correlates with increased biodiversity, supporting various organisms. The shape and size of an artificial reef can enhance its visual appeal and serve as a reference for specific species. Artificial reefs should be constructed to withstand displacement or overturning from towed gears, waves, currents, or erosion to ensure they fulfill their objectives. They should not be located in hurricane-prone areas and must consider existing activities like navigation, tourism, fishing, and conservation. Before installation, all stakeholders should be informed about the reef's characteristics, location, and depth.

Thus, the characteristics of blocks or modules—dimensions, size, mass, arrangement, and spacing should be designed based on the preferences of the target species. However, some main points can be made as follows [3, 11–13]:

- A modular reef is more accessible to transport and assemble, and it can attract more species and individuals.



COASTLINE

Consider the reef's proximity to the coastline for accessibility and environmental impact.

Analyze local coastal processes and sediment dynamics for the reef's effectiveness.

Evaluate how the reef will enhance coastal protection and reduce erosion.

Assess nearby recreational areas and amenities to maximize benefits from the reef.

WATER

Assess maximum, minimum, and mean water depths.

Determine the tidal period.

Analyze the direction and velocity of residual currents.

Examine wind and wave patterns.

OTHER ISSUES

Shipping lanes and anchorages for efficient maritime navigation.

Designated marine disposal sites for safe waste management.

Seabed pipelines to facilitate energy and resource transport.

Military exclusion zones, including ordnance disposal areas, to ensure safety.

Engineering applications of the seafloor for sustainable development and infrastructure solutions.

MARINE LIFE

Migration routes

Spawning and nursery areas

Preserving regions of beauty and historical value

Scientific importance of marine ecosystems and aids in biodiversity conservation

Fig. 2 Artificial reef design considerations

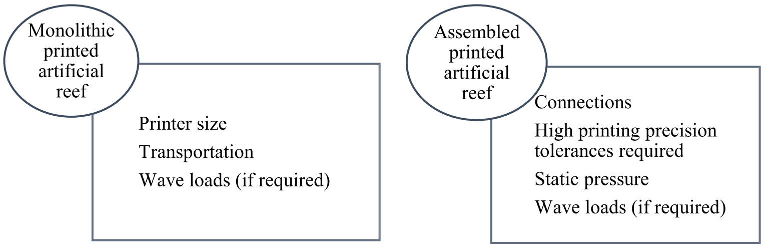
- Including small openings in reef structures is vital for the survival of young fish, as they prefer sizes that match their own.
- A larger surface area for algae and invertebrate settlement increases food sources for the reef community, enhancing overall productivity. The total available surface area is more crucial than size when determining reef biomass.

Reef structures must ensure proper water circulation. Thus, artificial reefs should meet their objectives while minimizing seabed use and disruption to natural marine ecosystems. Being subjected to a wave or static pressure load is not the most essential key of the artificial reef design. It should be considered in two cases: (1) a monolithic printed artificial reef and (2) an assembled printed artificial reef, as shown in Fig. 3. The biggest challenge in the first case is a more giant printer than the second case requires. However, the second case should consider some factors, as shown in Fig. 3 below. Among those factors, the authors will focus on the connection method for the configuration proposed in this study.

2.2 Details proposed model

Based on the design considerations discussed above, the authors employed 3D printing technology to create the reefs. The proposed configuration offers:

- Incorporating small openings is crucial for promoting the survival of both species and individual organisms.



Monolithic printed artificial reef

Printer size

Transportation

Wave loads (if required)

Assembled printed artificial reef

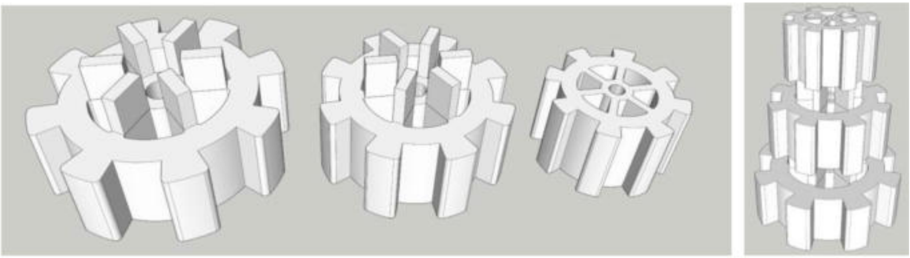
Connections

High printing precision tolerances required

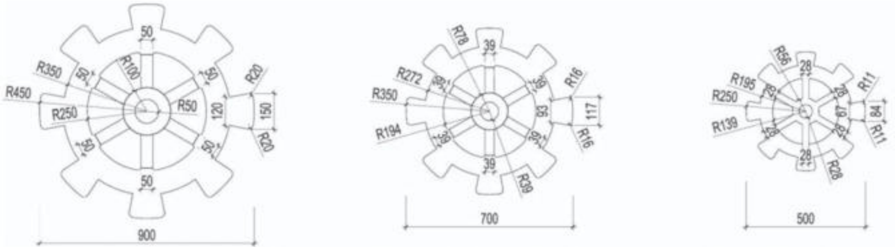
Static pressure

Wave loads (if required)

Fig. 3 Considerations in two cases of printing



(a) Base piece (b) Middle piece (c) Top piece (d) Single block



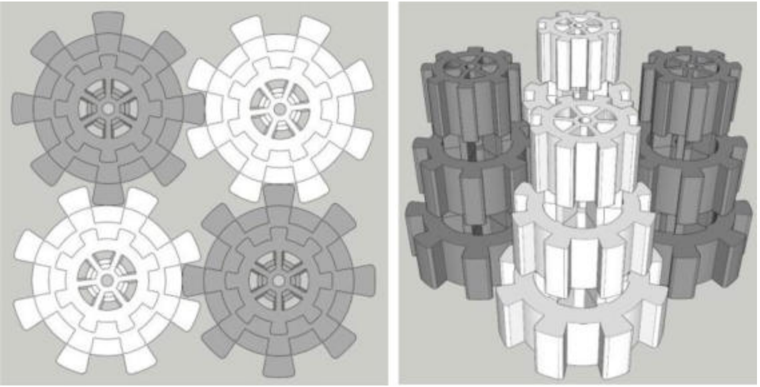
(e) Base piece (f) Middle piece (g) Top piece

Fig. 4 Design of a single block proposed in detail (unit: mm). **a** Base piece. **b** Middle piece. **c** Top piece. **d** Single block. **e** Base piece. **f** Middle piece. **g** Top piece

- Maximizing surface area and strategically designing reef structures and their cavities is essential for ensuring optimal water circulation.
- Artificial reefs must be designed for easy printing, transportation, and installation to maximize their impact and efficiency.
- The overall design of the reefs ensures they remain secure and stable against the forces of towed gears, waves, currents, and erosion, allowing them to fulfill their intended purpose consistently.
- Thanks to advanced printing technology, the surfaces of artificial reefs will feature a rough texture, providing significant benefits for marine plants like seaweed and moss and enhancing wave absorption.

The design of one single block contains three pieces: base, middle, and top pieces. Each piece includes six big holes, one small core hole, and eight gears, as shown in Fig. 4. The diameter of the base piece is 900 mm, the middle is 700 mm, and the top is 500 mm, as detailed in Fig. 4. The diameter of the single block decreases from base to top to create a stable configuration of the single block, as shown in Fig. 4(d).

Then, a module will contain four single blocks and interlock through the gears, as shown in Fig. 5. The dimension of a particular reef is multiplied by 1.8 m, formed by the module designed as shown in Fig. 5. A giant sea bed can be made up of coral reefs by using a module [14].



(a) Plan view (b) 3D view

Fig. 5 A module combined of four blocks. **a** Plan view. **b** 3D view

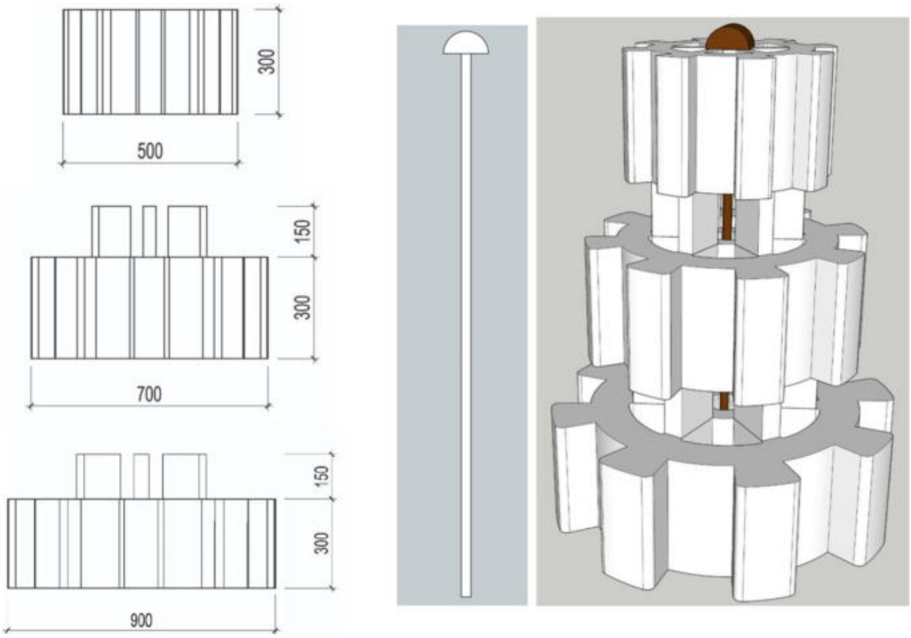
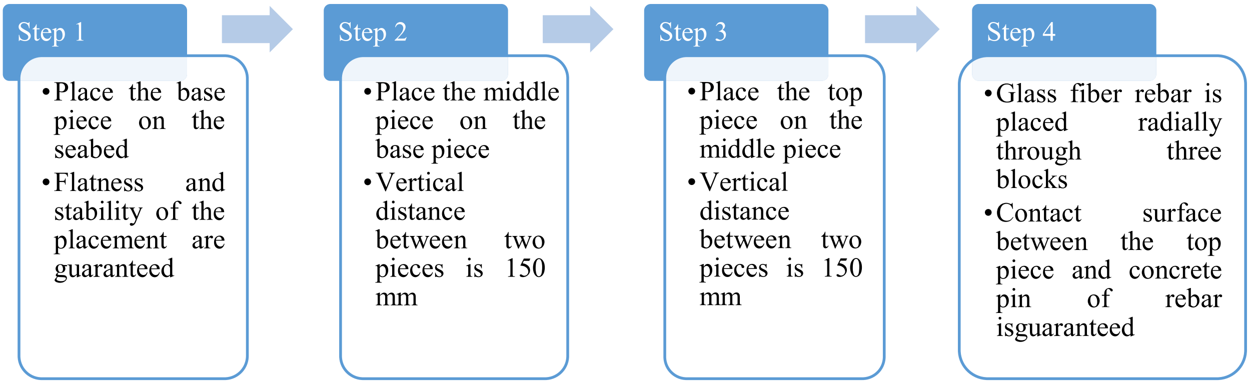


Fig. 6 Regulations with rebar connection method (unit: mm)

In this study, the authors offer two connection methods for a single block from the base, middle, and top pieces. The first solution is to use glass fiber rebar, which will be placed radially through three blocks. A concrete pin is at the top of the glass fiber rebar to stabilize when subjected to the water's vibration, as shown in Fig. 6. The process to assemble one single block is given in Fig. 7.

The second solution will employ an interlock detail, as shown in Fig. 8. The recessed part of the middle piece is inserted into the raised part of the base piece with a length of 150 mm, as shown in the bottom view in Fig. 8 when inserting the top piece into the middle piece. The process of assembly of one single block according to the second solution is given in Fig. 9.

The advantages and disadvantages of the two suggested solutions are given. The solution using glass fiber rebar will be more expensive based on the price of the glass fiber rebar, and the assembling process contains four steps, which will take more time to build up the artificial reef. However, precise requirements in printing tasks are not limited to the width of the filament, as there is no insertion between the two pieces. The only contact surfaces between the pieces are considered. In contrast, the second solution consumes only concrete material, resulting in an assembly process involving only three steps. The second solution sounds more efficient in terms of material consumption and time. Compared to the first solution, the only disadvantage is the exact requirements for printing tasks because there are



Step 1
- Place the base piece on the seabed
- Flatness and stability of the placement are guaranteed

Step 2
- Place the middle piece on the base piece
- Vertical distance between two pieces is 150 mm

Step 3
- Place the top piece on the middle piece
- Vertical distance between two pieces is 150 mm

Step 4
- Glass fiber rebar is placed radially through three blocks
- Contact surface between the top piece and concrete pin of rebar isguaranteed

Fig. 7 Assembling process using the rebar connection method

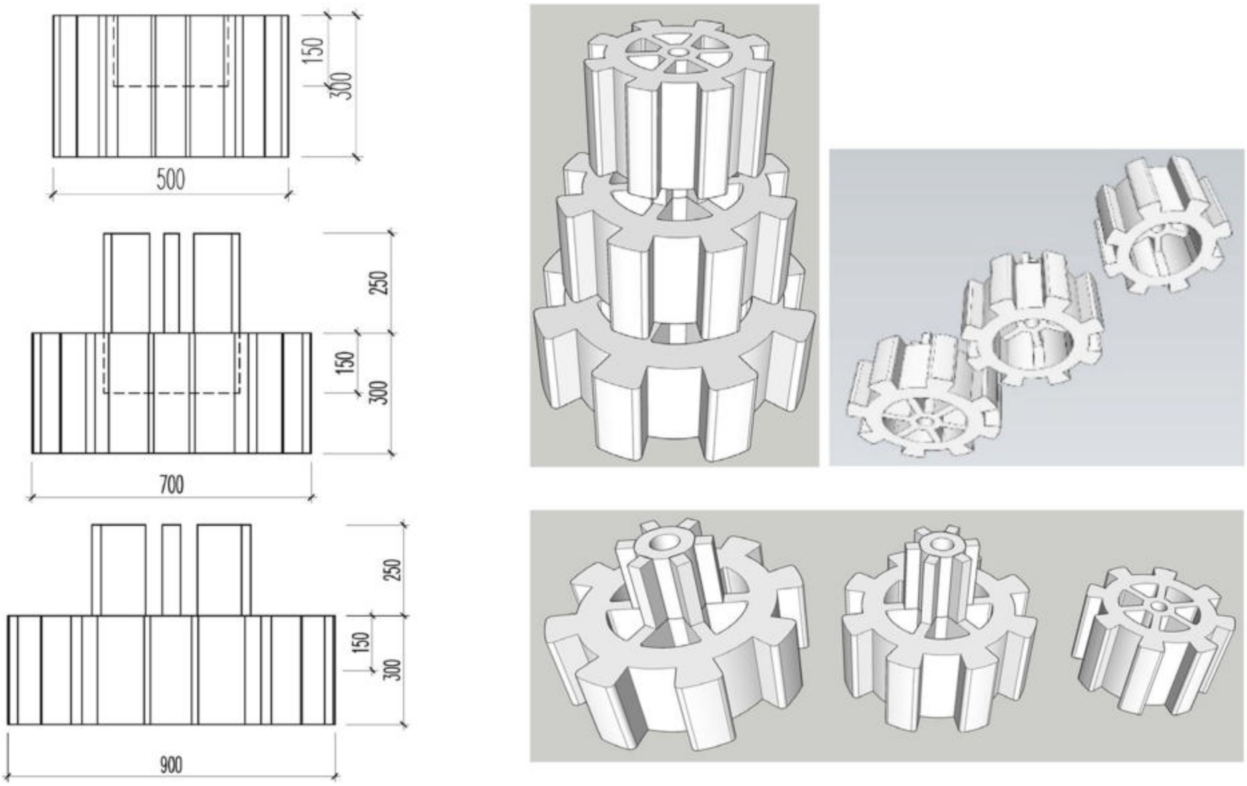


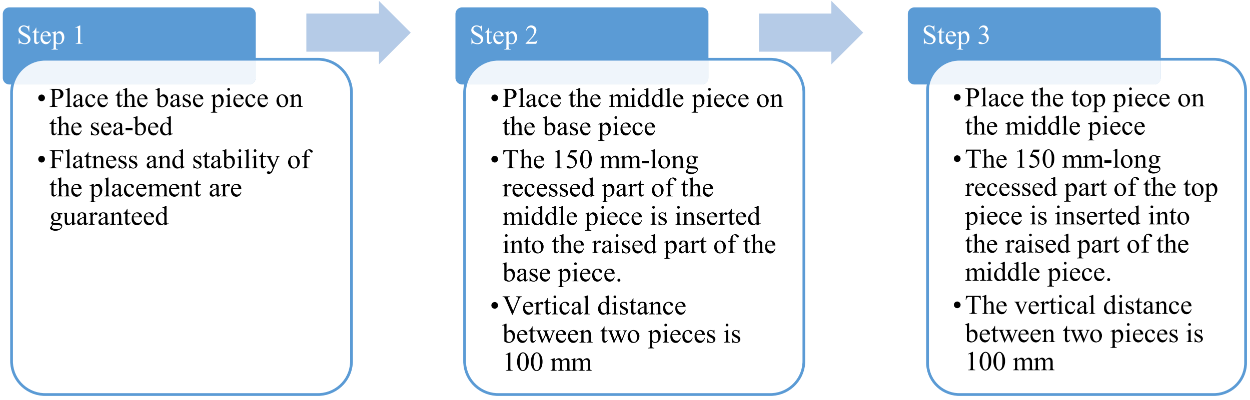
Fig. 8 Regulations without the rebar connection method (unit: mm)

insertions among pieces, as described above. By applying 3D printing in manufacturing, this disadvantage can certainly be overcome.

3 Materials and mix proportions

The main goal in selecting reef materials is to ensure effectiveness while meeting safety and environmental standards. In general:

- Artificial reefs must be constructed using environmentally sustainable materials for the health of our ecosystems.
- The materials must be inert and resistant to seawater deterioration, ensuring they do not pollute through leaching, weathering, or biological activity.
- Material selection directly influences reef colonization, and it is crucial to account for biological factors, particularly the feeding preferences of target species.



Step 1

- Place the base piece on the sea-bed
- Flatness and stability of the placement are guaranteed

Step 2

- Place the middle piece on the base piece
- The 150 mm-long recessed part of the middle piece is inserted into the raised part of the base piece.
- Vertical distance between two pieces is 100 mm

Step 3

- Place the top piece on the middle piece
- The 150 mm-long recessed part of the top piece is inserted into the raised part of the middle piece.
- The vertical distance between two pieces is 100 mm

Fig. 9 Assembling process without the rebar connection method

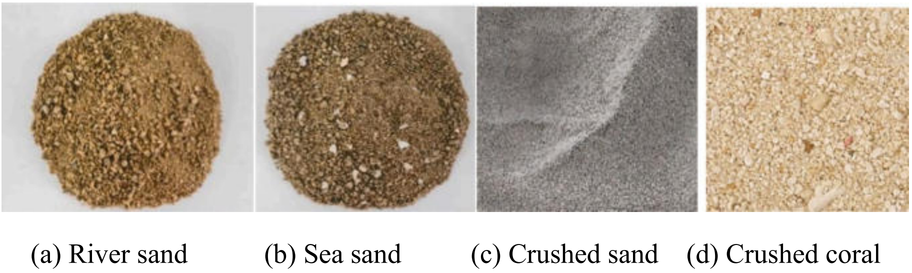


Fig. 10 Sand kinds. **a** River sand. **b** Sea sand. **c** Crushed sand. **d** Crushed coral

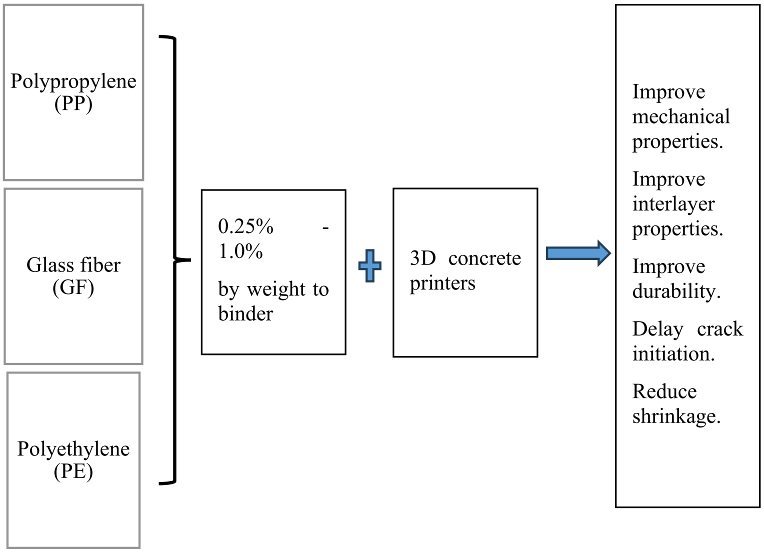


Fig. 11 Recommended fibers and effectiveness

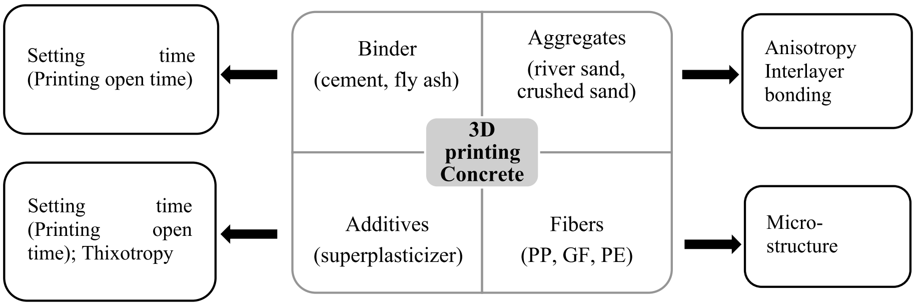


Fig. 12 Constituent material roles in the concrete matrix

Artificial reefs can be constructed from natural, recycled, or prefabricated materials, with the latter offering the benefit of customization. Concrete is often the preferred choice due to its durability, flexibility, stability, and texture, which resembles that of natural reefs. There is undeniable potential in leveraging sustainable materials, specifically recycled, eco-friendly, and low-carbon options [15–17]. Recent monitoring of artificial reefs has definitively highlighted the advantages and drawbacks of various construction materials. Researchers strongly advocate for the use of fly ash as a critical component in optimizing cement [18, 19]. This byproduct from coal-fired boilers enhances concrete by improving workability, placement, pumping, and finishing efficiency. It reduces water demand and drying shrinkage, significantly boosts long-term compressive strength, and increases durability,

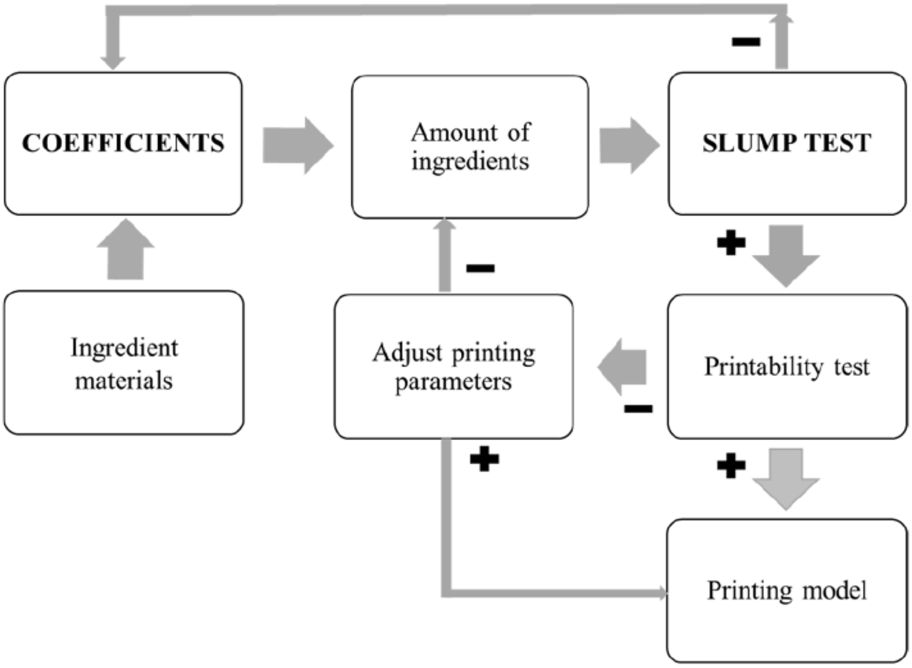


Fig. 13 Mix proportion design process

offering resistance to sulfate, chloride, and alkali-silica reactions.

For optimal 3D printing results, fine aggregates with an average hole diameter smaller than 2.5 mm are essential. These finely sieved materials, sourced from river or sea sand, crushed sand, or coral, significantly enhance the quality and precision of printed structures, making them indispensable for high-performance applications, as shown in Fig. 10.

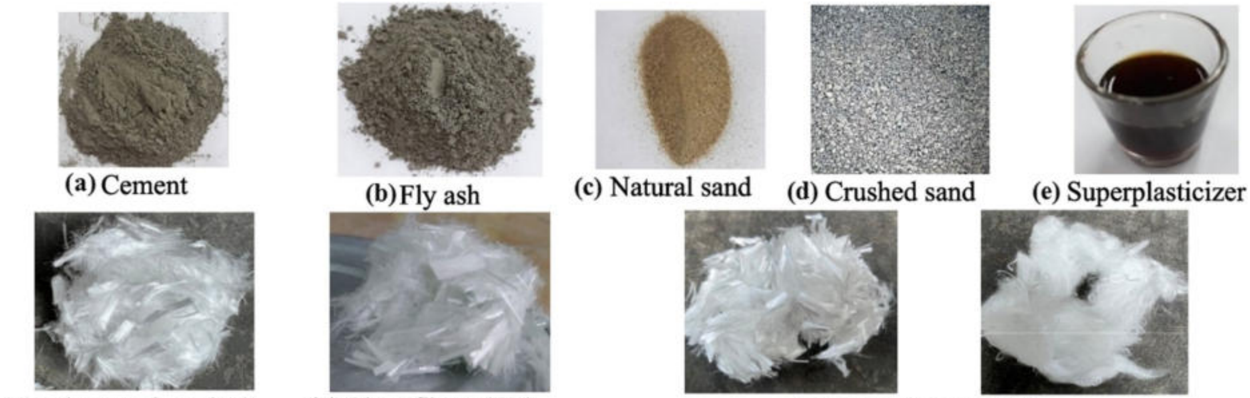
Crushed sand, artificial sand produced by crushing basalt and granite, guarantees a consistent grain size through a fixed sieve. Adhering to proper production methods minimizes the risk of adulteration. This study underscores that crushed sand is primarily sourced from granite, reinforcing its quality and reliability for various applications.

Concrete, a cement-based composite, consists of cement as a binder, coarse aggregate as a framework, fine aggregate, fly ash as a filler, and water and other additives. It is prone to developing cracks and fissures under tensile or flexural loading due to its inherent lack of toughness, ultimately leading to failure. In recent decades, the demand for high-performance materials in civil engineering has intensified, driven by stringent safety, cost, and sustainability requirements. Fiber-reinforced concrete (FRC) has firmly established itself as a leading material in civil engineering thanks to its significant advantages, including (1) toughness in assessing compressive and flexural bending strength, (2) tensile strength, (3) durability, and (4) energy-absorbing capacity. Fibrous reinforcement in concrete is often viewed as a cost-effective option, as it reduces installation times compared to conventional reinforcement. FRC is also advantageous for

Table 1 Mix proportions

Mix label	Cement	Fly ash	Water	Natural sand	Crushed sand	Fiber	SP
M-PP	0.75	0.25	0.32	0.5 (1.25 mm)	0.5 (2.5 mm)	0.25	0.4
M-GF	0.75	0.25	0.32	0.5 (1.25 mm)	0.5 (2.5 mm)	0.25	0.4
M-PE	0.75	0.25	0.32	0.5 (1.25 mm)	0.5 (2.5 mm)	0.25	0.4

Note: binder = cement and fly ash; values in Table are ratios of each ingredient to binder mass



(a) Cement (b) Fly ash (c) Natural sand (d) Crushed sand (e) Superplasticizer

(f) Polypropylene (PP) (g) Glass fibers (GF) (h) Polyethylene (PE)

Fig. 14 Materials used for mixing concrete. **a** Cement. **b** Fly ash. **c** Natural sand. **d** Crushed sand. **e** Superplasticizer. **f** Polypropylene (PP). **g** Glass fibers (GF). **h** Polyethylene (PE)

Fig. 15 Slump tests

(a) Printed samples (b) Flexural test (c) Compressive test

Fig. 16 Test for anisotropic behavior of 3D printed concrete. **a** Printed samples. **b** Flexural test. **c** Compressive test

casting since the fibers are mixed in beforehand. FRC has proven successful in various engineering applications due to its strong performance in construction and industry. Recent studies on FRC have concentrated on the influence of fibers on its mechanical behavior. The incorporation of fibers can modify essential properties, including residual strength, tensile splitting strength, and flexural strength following exposure to heat [17–21]. Polypropylene (PP), polyethylene (PE), and glass fiber (GF) are gaining attention for their low cost, lightweight, corrosion resistance, toughness, and shrinkage cracking resistance. Recently, these chopped synthetic fibers have been used

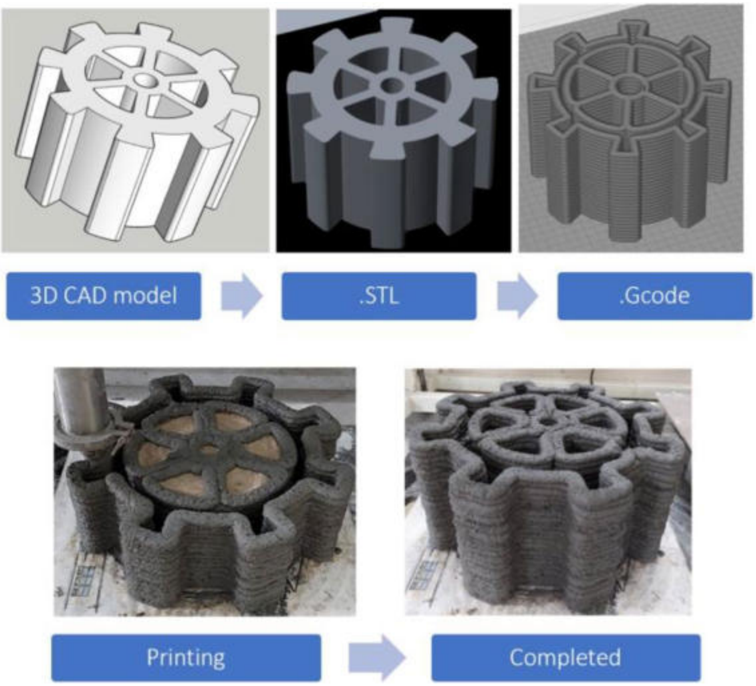
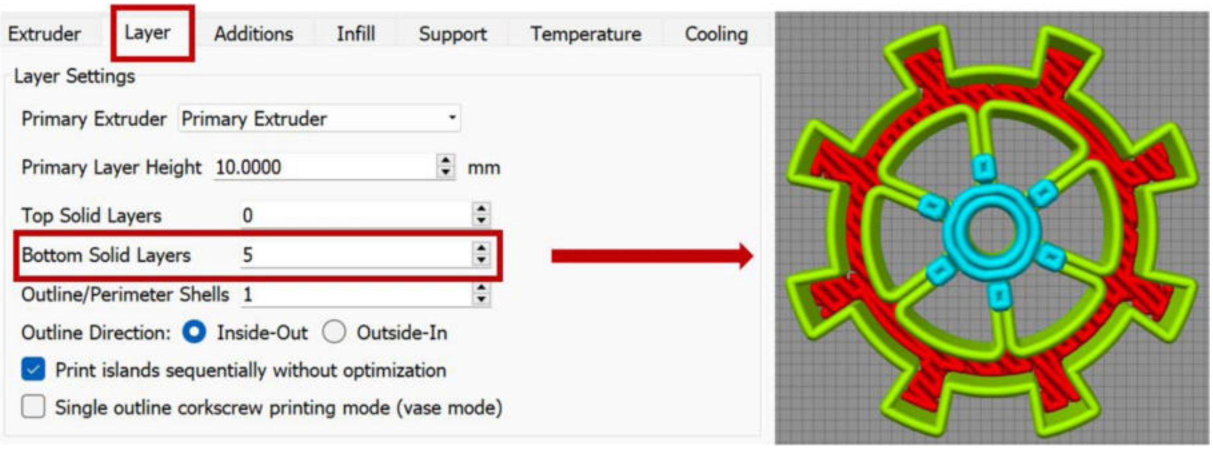


Fig. 17 Printing process

as reinforcement in concrete to improve its mechanical properties. In conclusion, the selected fiber to reinforced concrete in this study with a suggested amount can be concise in Fig. 11.

The performance of a printed structure is contingent upon the effective maintenance of the process across varying conditions. Typically, the 3DCP mixture comprises binders, admixtures, fine aggregates, and fibers. The efficacy of a composite concrete mix is influenced by the constituent materials, their proportions, strength, and the bond mechanisms within the matrix. Therefore, it is essential to understand the significance of each material's role in determining both the fresh and hardened properties of the concrete, as illustrated in Fig. 12. All constituent materials influence the workability, shrinkage, and mechanical properties of concrete. In the context of 3D printed concrete, the printing open time or setting time designates the duration for which the material remains workable during the printing process. This parameter is essential for assessing the performance of 3D printing materials, as it significantly affects the buildability and extrudability of the concrete mixtures. A longer setting time facilitates improved fluidity and extrudability, while a shorter time contributes to adequate early strength.



Layer Settings

Primary Extruder: Primary Extruder

Primary Layer Height 10.0000 mm

Top Solid Layers 0

Bottom Solid Layers 5

Outline/Perimeter Shells 1

Outline Direction: ● Inside-Out ○ Outside-In

☑ Print islands sequentially without optimization

☐ Single outline corkscrew printing mode (vase mode)

Fig. 18 The technical command inside Simplify3D

Fig. 19 Printed pieces

Based on the above analysis of constitution materials, the authors employed the mix design process in Fig. 13 [22] to determine the proportion of each material in Table 1. Figure 14 demonstrates materials used in the study.

The authors' mix design method resulted in slump values of 10 mm to 30 mm, with slight deformation of the concrete shape after lifting the mold, as shown in Fig. 15, which confirms the best extruding and printing quality. The extrudability of concrete, as determined through tests conducted on three printers, is influenced by several key factors:

- The mix proportions, including the water-binder ratio, aggregate characteristics, and dosage of chemical admixtures;
- The relationship between the diameters of the nozzle and aggregates;
- The interplay between the mix proportions and printing parameters, particularly the extrusion speed.

Fig. 20 Printed artificial coral reefs

3D-printed specimens exhibit anisotropic behavior. The compressive strength is maximized in the direction parallel to the filaments within the printing plane, while strengths in all other directions are notably lower [23–25]. The results align with the authors' investigations. A study on the anisotropic behavior of 3D-printed concrete is presented in Fig. 16.

4 Trial productions

4.1 Manufacturing process

The process begins with a 3D CAD model saved in ".STL" format. This model is then sliced into layers using Simplify3D software, resulting in a ".Gcode" file that the 3D printer can read. Ultimately, 3D concrete printers, operated with Mach3 software, fabricate the components by building them layer by layer through selective material placement. Figure 17 illustrates the process presented above.

To connect the outer and inner layers, click "Edit Process Settings", then in the "Layer" tab, five or more bottom solid layers are defined, as illustrated in Fig. 18.

The circle nozzle diameter of 22 mm was used to print three pieces of the single block, as shown in Fig. 19. The total printing time was around 150 min.

4.2 Assembling

According to the assembly process of one block in Sect. 2.3, to achieve optimal results, the three printed pieces were skillfully combined into a single block, as demonstrated in Fig. 20. The block weighs approximately 300 kg and is divided into three pieces so that two to three people can easily lift each piece.

5 Conclusions

From an idea to design and manufacture, the study brings insight into 3D concrete printing technology to a case study of artificial coral reefs. Based on the research objectives and limitations, the highlighted conclusions can be given as follows:

- Concrete printing technology creates coral reef surfaces with arbitrary roughness and complex structures, an effective solution for producing coral reefs similar to natural ones.
- Complex structures significantly enhance species diversity on the reef, providing vital settlement, shelter, feeding, and breeding grounds.
- Rough and irregular surfaces, along with pores and cavities similar to those found in natural rock, are critical in attracting organisms to the reef.
- The proposed design shape successfully trialed in this research can be used as a reference model.

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Authors' contributions
Jie Yi Huang has been responsible for conceptualization and Methodology; Loan Thi Pham has been responsible for the designed models and experimental program, Writing original draft preparation, and Editing. All authors read and approved the final manuscript.

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All data generated or analyzed during this study are included in this article and available from the corresponding author upon reasonable request.

Declarations

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Consent for publication
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