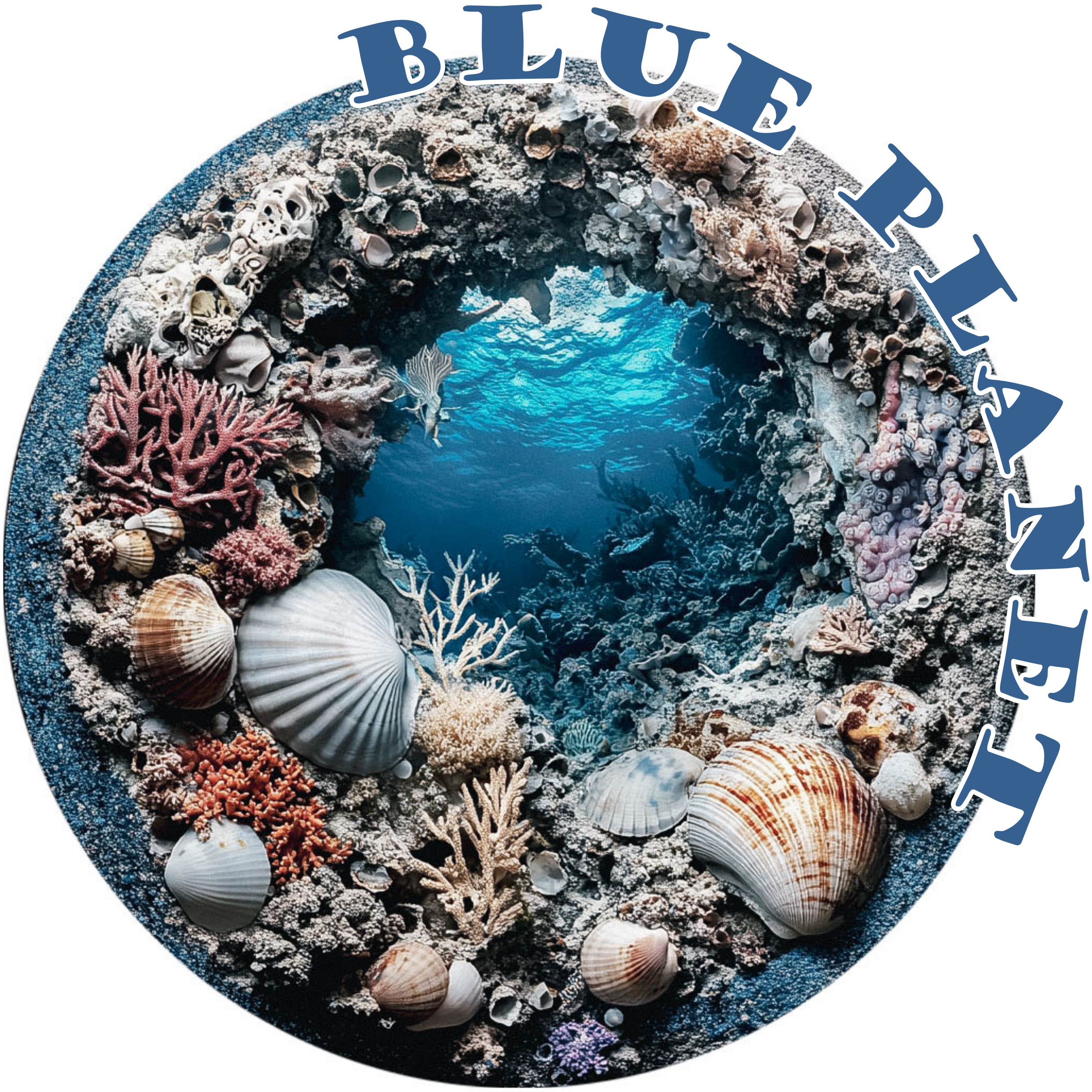

Hybrid Solutions for Underwater Structures with Seashell Concrete and Biorock Technology

Xiaojun Zhu
Chalmers School of Architecture | Department of Architecture and Civil Engineering
Master's Thesis 2025
Examiner: Jonas Lundberg | Supervisor:Jonas Lundberg

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BLUE PLANET

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Architecture and Urban Design
Architectural Experimentation
Matter and Media

Chalmers University of Technology
Gothenburg, Sweden

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ACKNOWLEDGMENTS

I would like to express my sincere gratitude to my supervisor, Jonas Lundberg, for all his support, guidance, and encouragement throughout my master's research. His feedback and insights during the tutorials helped me determine and shape the direction of my master's thesis. Thanks to Kengo Skorick, Mimmi Amini, and other academic tutors and colleagues for their valuable input and help on my thesis during the different phases of the seminars. Also, many thanks to Peter Lindblom and Tabita Nilsson for the instructions and help with my work in the workshop.

Further, I would like to express my heartfelt thanks to Emmanouela Leventaki, a doctoral student in Chemistry and Chemical Engineering at Chalmers University of Technology, for helping me with seashell calcination and some basic chemistry knowledge. Also, to my friend Guokang Li, a master's student in Materials Engineering at Chalmers, for showing me the basic information about electrolysis and helping me when I faced difficulties during the biorock mineral accretion experiment.

Finally, I want to thank my family for their endless love and support. Even though we are far apart, I can always feel their support and encouragement. I would also like to thank my friends in Sweden and China for always being there during my difficult and stressful times and for telling me, "Chloe, you are the best! You can do it!", when I was not confident, which allowed me to convince me that I would be able to make it through this very stressful but fun journey of master's thesis.

ABSTRACT

Global sea levels are predicted to rise by up to 2 meters by 2100 due to the high rates of carbon emissions, which lead to frequent flooding, eventually making coastal cities uninhabitable (NOAA, 2022).

This thesis explores how seashell waste, in combination with the process of biorock technology (mineral accretion), can be turned into a hybrid material system Furthermore, it investigates how this hybrid material be utilized for load-bearing underwater structures.

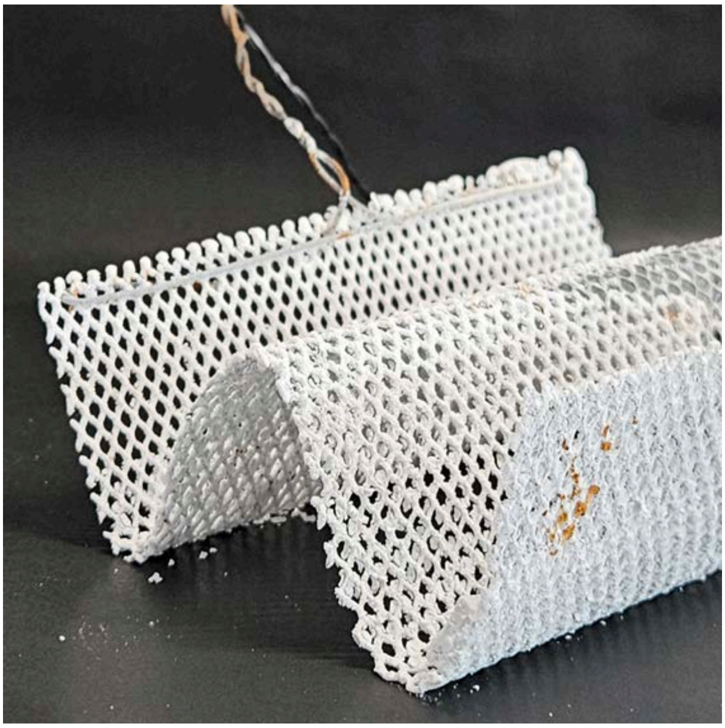
Seashell concrete, derived from recycled seashell waste, is ground and calcined to replace traditional aggregates and Portland cement, reducing carbon emissions by 50% compared to traditional concrete(Crook, L., 2024). Biorock technology - a process of mineral accretion, meanwhile, uses seawater electrolysis to grow limestone, creating a material around three times stronger than traditional concrete while promoting coral reef restoration (Goreau, T.J., 2012).

The material experiments test the properties of each material and the potential of hybrid material compositions. While seashell concrete alone lacks the compressive strength of traditional concrete, reinforcing it with biorock technology compensates for this weakness, potentially meeting the load-bearing requirement for underwater construction.

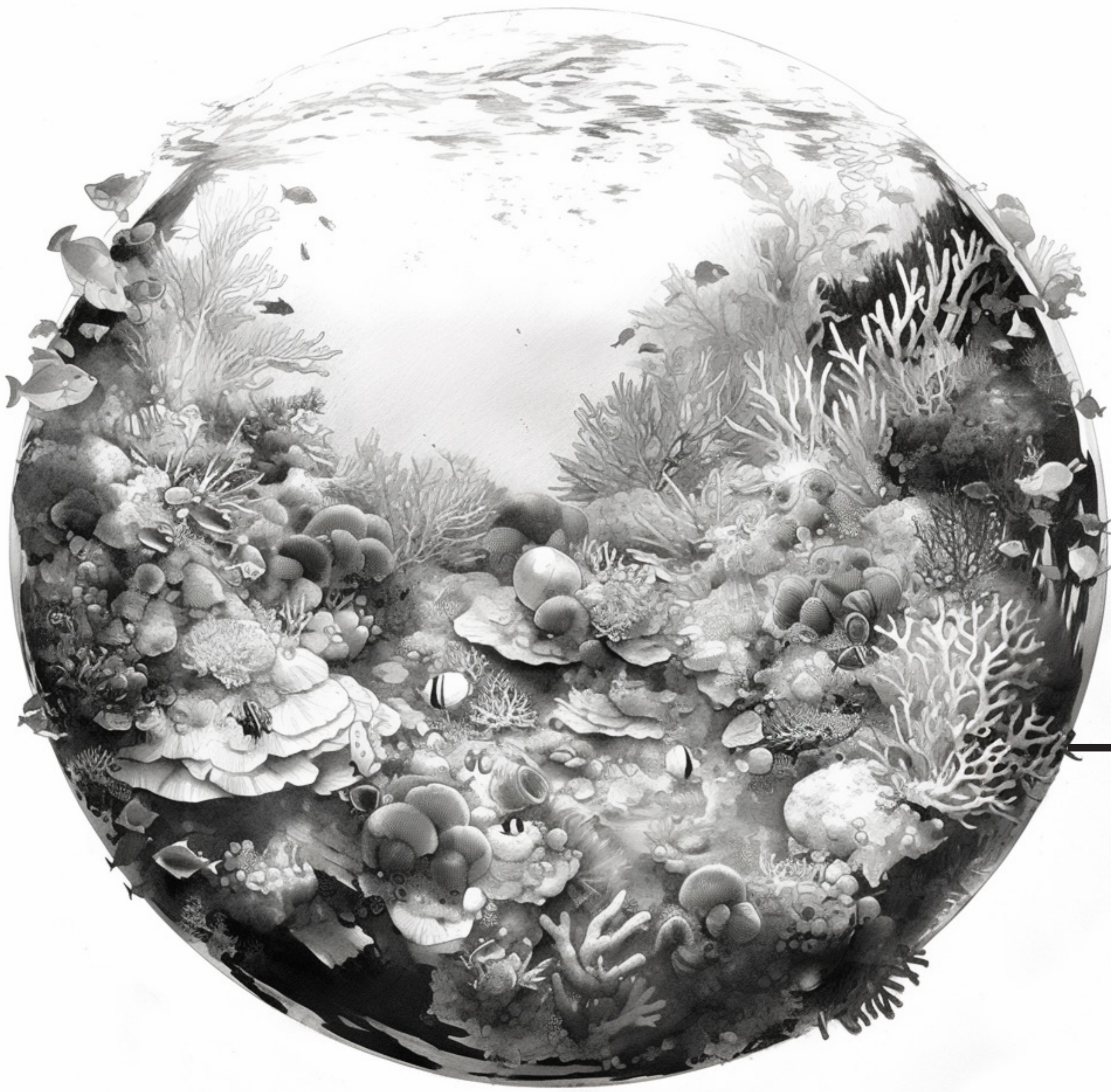
The design proposal transforms the Montipora coral's layered and radial form into a modular underwater experimental building prototype at Dhangethi Jetty, Maldives. Computation tools shaped the geometry and created the structure, which has helped explore coral-like forms and simulate how limestone grows through mineral accretion. This coral-inspired structure, combined with biorock technology, creates a habitat for coral polyps and transforms the building itself into a living reef.

By merging this hybrid material innovation with coral reef restoration, the project offers a blueprint for future coastal cities. It demonstrates how architecture can adapt to sea level rise, reduce reliance on carbon-intensive concrete, and actively rebuild ecosystems - proving that human habitats can work with and even foster marine life.

Keywords: seashell concrete, biorock technology, hybrid material, coral restoration, underwater architecture, sea-level rise



CONTENT



INTRODUCTION

Background

Global Warming and Sea-Level Rise

Global warming will continue to affect us, and this is something we can appreciate not only from the rising temperatures year after year, but also from the studies of surface temperature data from NOAA NCEI, all of which show the trend of rising global temperatures. Carbon dioxide produced by human activities, such as the burning of fossil fuels and deforestation, is the most significant contributor to global warming. The construction industry is one of the largest emitters of carbon dioxide. The carbon dioxide emissions caused by the built environment account for about 42% of the annual global carbon dioxide emissions (Architecture 2030, n.d.), where some of the construction materials emit large amounts of carbon dioxide from the production process that consumes large amounts of fossil fuels, such as cement, iron, steel and aluminium. As the concentration of carbon dioxide in the atmosphere increases, global temperatures rise, leading to the melting of water from glaciers and polar ice caps and the thermal expansion of seawater, which contributes to rising sea level water levels(Lindsey, R, 2023). In its 2022 report, NOAA predicts that by the year 2100, global mean sea level will have risen by at least 0.3 m (Figure 1) above the year 2000 level. Sea levels could be as much as 2 meters higher in 2100 than they were in 2000 because of very high rates of emissions, which can trigger rapid ice sheet collapse. This figure is very dangerous for coastal cities because of the coastal flooding and habitat loss that accompanies sea level rise.

Urbanization and Land Scarcity

As the world's population grows every year, more and more people will move to cities in search of better opportunities, which means that urbanization will continue to grow. In its 2018 report on the World Urbanization Perspective, the United Nations predicted that by 2050, close to 68% of the global population will live in urban areas. The dramatic increase in urban population leads to an increased demand for housing, meaning we will need more land resources to build homes with higher and higher floors. As a result, there will be more forests, and agricultural land will be opened up for urban development. The result of this expansion is that our land resources are becoming increasingly scarce, and it is also destroying the biodiversity of nature while further exacerbating the greenhouse effect, making the environment on which we depend for our survival worse and worse.

Ocean and Sea

About 71% of the Earth's surface is covered by water, and the oceans contain about 96.5% (Figure 2) of the Earth's water (Igor Shiklamonov, 1993). This data illustrates that the oceans contain an abundance of resources and materials we can use, most of which we have yet to exploit. According to the High Level Panel for a Sustainable Ocean Economy (2019), renewable energy can be generated through offshore wind (OSW) energy, wave energy, tidal stream, thermal gradient, salinity gradient and other technologies, which can make offshore cities self-sufficient in terms of energy. In addition to this, according to Global Carbon Budget 2022 by Friedlingstein et al. (2022), the oceans can absorb approximately 27% of atmospheric carbon dioxide produced by fossil fuels each year and capture excess heat from these emissions, making them our most significant carbon sink and providing some protection against the effects of global warming.

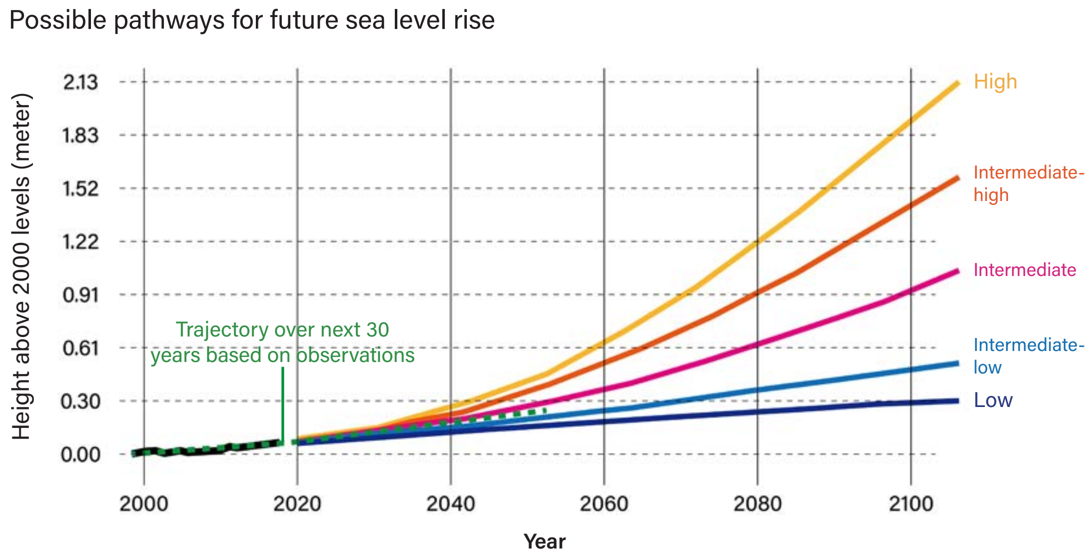


Fig.1: *Observed and projected global sea level rise (2000–2100) under six future greenhouse gas pathways. Redrawn by the author. (Source: NOAA Climate.gov graph, adapted from Sweet et al., 2022. https://www.climate.gov/media/14136)*

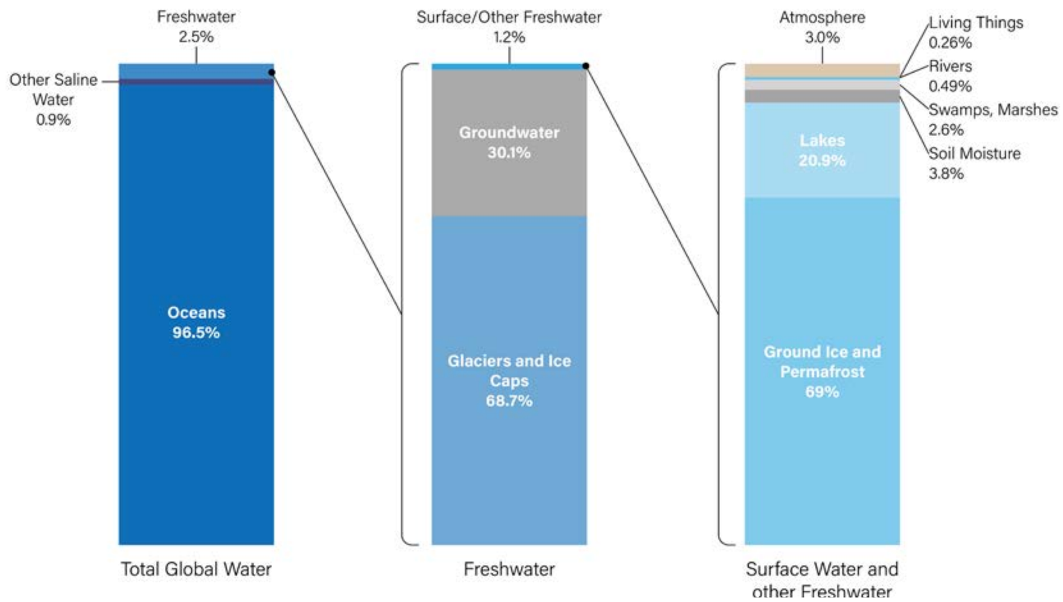


Fig.2: *Where is Earth's Water? Redrawn by the author. (Source: Igor Shiklomanov's chapter "World fresh water resources" in Peter H. Gleick (editor), 1993, Water in Crisis: A Guide to the World's Fresh Water Resources.)*

Coral Reef

Coral reefs are one of the most diverse ecosystems on the planet and are also known as marine rainforests. Although they cover less than 1% of the seabed, they provide a habitat for up to 25% of the world's marine species (Mulhall, M, 2009). According to the NOAA Coral Reef Conservation Program (n.d.), each coral is a colony of multiple small, similar coral polyps, which utilize calcium and carbonate from seawater to build their skeletons, forming the structure of coral reefs, which become marine habitats providing food and shelter for phytoplankton, as well as marine organisms and more. Coral reefs form a symbiotic relationship with the wormwood algae, which absorbs carbon dioxide and releases it through photosynthesis (Hilbertz, W. H, 1992). However, as global warming increases carbon dioxide levels, the amount of carbon dioxide absorbed by the oceans also increases, which, in combination with various ions in the seawater, leads to a number of chemical reactions, causing the pH of the seawater to drop and the oceans to become more acidic, a phenomenon also known as ocean acidification. This phenomenon is also known as ocean acidification. Ocean acidification affects shells, oysters, and corals, which form their shells and skeletons by combining calcium and carbonates from seawater. If the pH is too low, the shells and skeletons begin to dissolve, leading to a decrease in the number of coral reefs, which in turn destroys one of the ocean's most important ecosystems ((Mulhall, M, 2009).

Seashell Waste

Seashell waste is a potential sustainable building material. However, a large amount of shells produced each year, especially oysters, mussels and scallops, end up on beaches, in open fields or landfills, and only a very small portion of them are reused for crafts or fertilizers. Moreover, many discarded shells produce bad odors when they decompose, leading to environmental pollution problems (Mo et al., 2018).

Apart from the seashell waste in the natural environment, the seafood industry also generates large amounts of shell waste. Take oysters for example, it is estimated that 5 million tons of them are discarded every year (Bellei et al., 2023), which are then piled up or landfilled, creating serious environmental problems.

The main component of most shells is calcium carbonate, which, when calcined at high temperatures, turns into calcium oxide, the main component of cement. Compared to Portland cement, making cement from shell waste produces much less carbon dioxide, reducing the carbon footprint to some extent. In addition to being calcined at high temperatures to become the raw material for cement, shell waste can also be used as coarse and fine aggregates in the concrete making process, which can improve the compressive strength of concrete (Mo et al., 2018).

Problem Description

As global temperatures continue to warm, rising sea levels are unavoidable, which leads to frequent flooding and ultimately makes coastal cities uninhabitable. Moreover, with the gradual population growth and rapid urbanization leading to land scarcity. If this situation goes to extremes, there will come a time when the ocean submerges all land. This is when underwater buildings and structures offer an alternative way of living. More importantly, we all know that most of the earth's surface is covered by water, with the oceans accounting for 96.5% of the total water (Igor Shiklamonov, 1993). Consequently, there is an abundance of resources and materials we can use from the ocean, and people living underwater can be realized with a greater likelihood.

When it comes to underwater construction, concrete and steel are the essential materials that can resist underwater environmental problems such as seawater pressure and corrosion. However, they are also one of the 'culprits 'of global warming due to massive carbon dioxide emissions that are produced during the manufacturing process. In order to realize the goals put forward by the European Commission, which is to achieve zero greenhouse gas(GHG) emissions by 2050, many strategies have been proposed, including reducing GHG emissions in construction, discovering new sustainable materials such as bio-based and recycled materials.

In this context, seashell concrete offers a sustainable alternative to concrete solutions. Seashells are mainly composed of calcium carbonate ($CaCO_3$), which can be calcined at high temperatures to form calcium oxide (CaO), one of the main components of cement, but this process produces half the carbon dioxide emissions of cement (Crook, L., 2020). Therefore, the carbon footprint can be reduced by recycling discarded seashells as aggregates in concrete or as a partial replacement for cement. However, concrete made from waste seashells is not as strong as traditional concrete (Mo et al., 2018), and therefore is mostly suitable for decorative purposes and cannot be used for large or structural projects (Crook, L., 2020).

In addition, biorock technology offers a sustainable material for underwater construction. Discovered by architect Wolf Hilbertz, the technology uses an electrolytic reaction to deposit calcium and carbonate ions from seawater onto a metal wire mesh attached to a cathode. Over time, this structure attracts marine organisms such as corals to settle down, promoting coral reef restoration (Hilbertz, W., 1991). According to Wolf Hilbertz. (1979), materials generated by biorock technology can be as strong as traditional concrete. However, there are very few cases of using this material for construction projects, and it is more commonly used for artificial reefs and small lightweight structures.

Integrating seashell concrete and biorock technology provides hybrid solutions for underwater construction. Biorock technology can compensate for the lack of strength of seashell concrete, and the combination of seashell concrete and biorock technology offers potential and possibilities for underwater large-scale projects or load-bearing structures. This hybrid solution not only reduces carbon emissions and contributes to the restoration of marine ecosystems, but also opens up possibilities for underwater construction, addressing the issues of global warming, rising sea levels and land scarcity.

Aim

This thesis investigates the possibilities and potential of a hybrid material combining seashell concrete and biorock technology for underwater construction. It hopes to explore through experimental tests, the possibilities of the hybrid material as a load-bearing structure, especially for underwater construction. The final goal is to be able to design an underwater building that utilizes hybrid material as a load-bearing structural material.

Research Question

- How can seashell waste be used as a sustainable alternative to traditional concrete?
- How can hybrid materials using seashell concrete and biorock technology be utilized for load-bearing structural purposes?
- How can an underwater building be constructed by using this hybrid material combining seashell concrete and biorock technology?

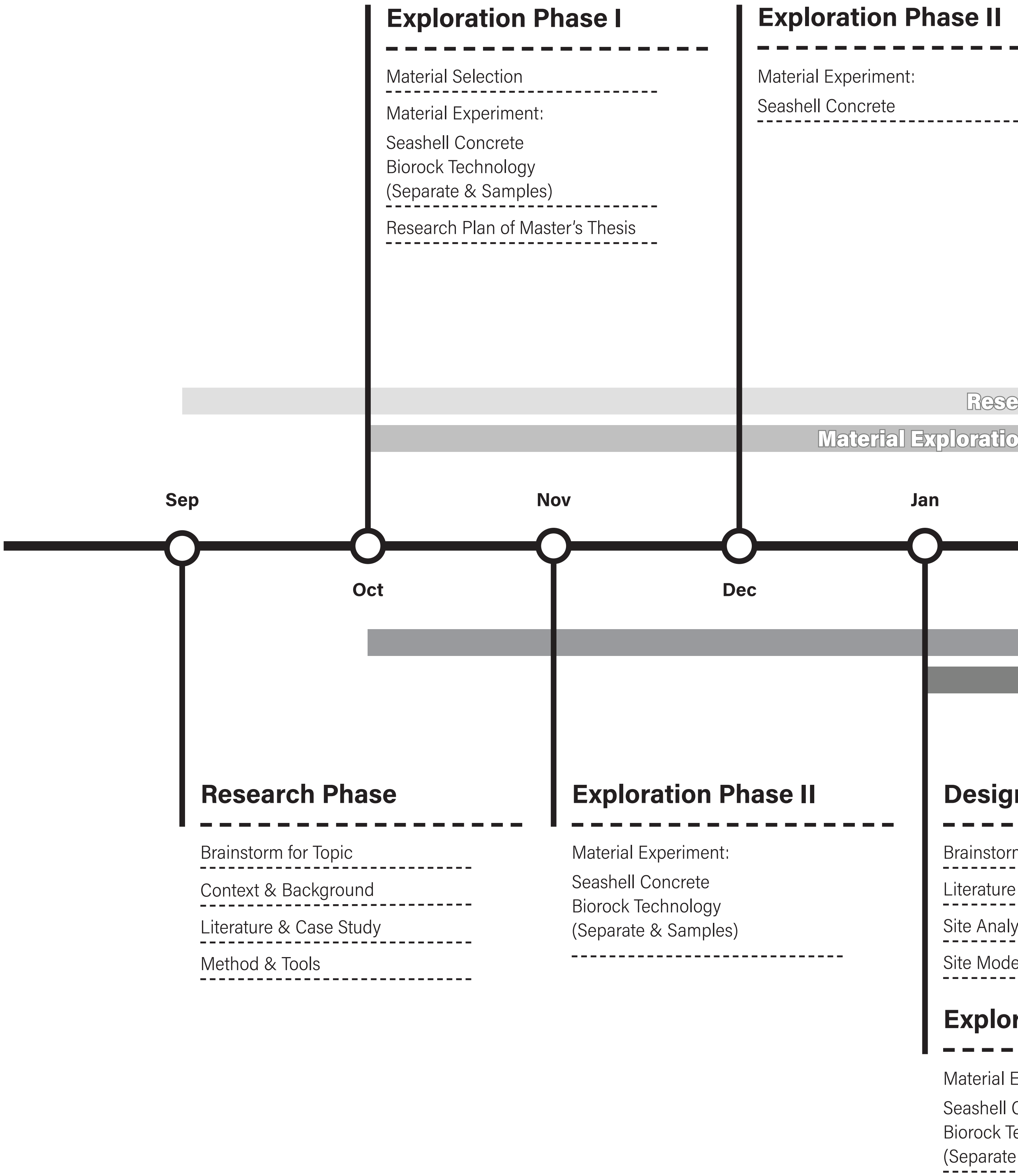
Relevance for Sustainable Development

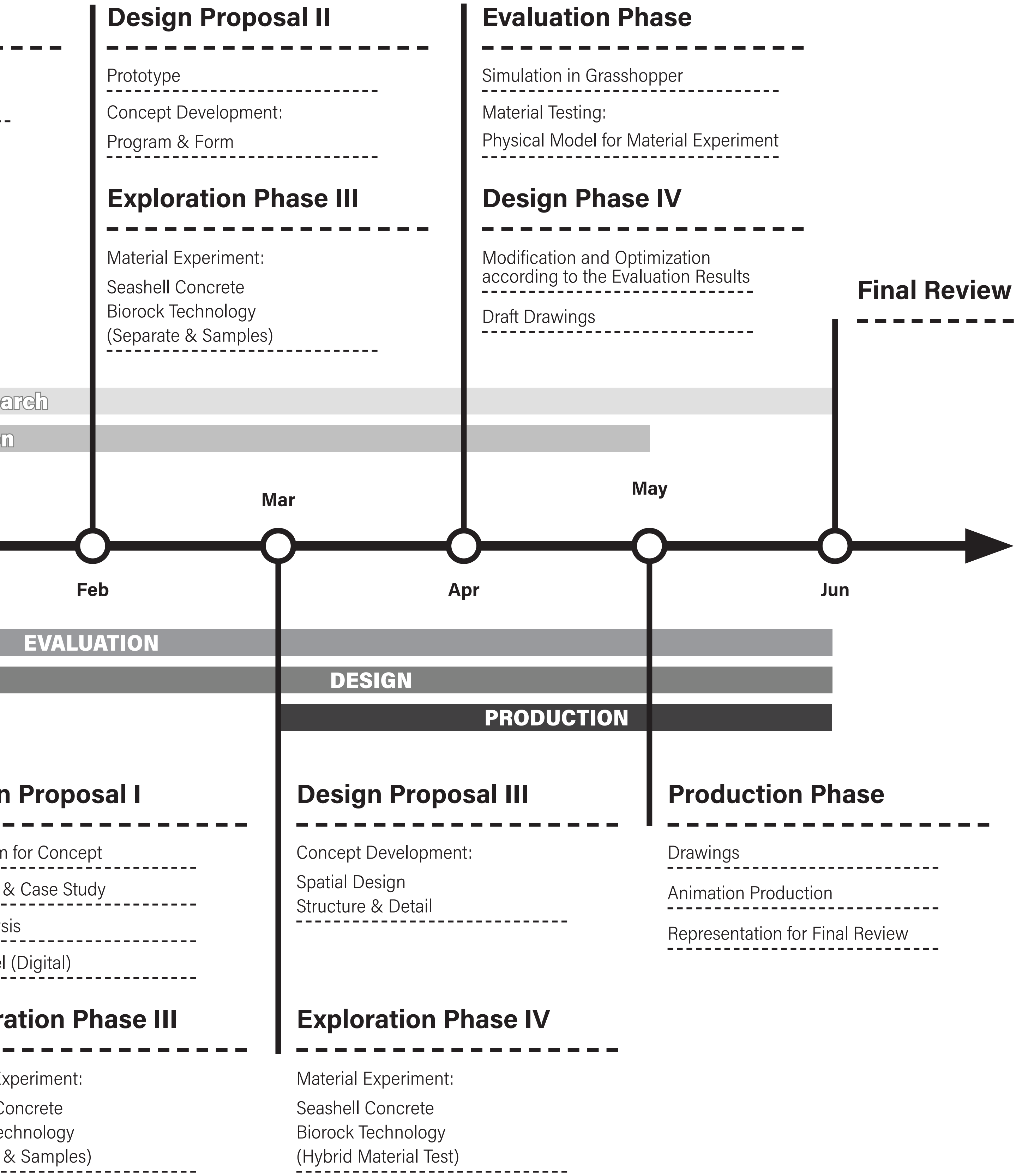
This thesis explores the application of hybrid materials in underwater building construction, combining seashell concrete and biorock technology to discover environmentally friendly building materials that can reduce carbon footprints. While one of the two materials is concrete and the other is a steel-based limestone material formed through an electrolytic mineral accretion. The production of seashell concrete produces half the carbon dioxide compared to that of traditional concrete, and the biorock technology further protects the steel from seawater erosion and reduces the need for steel for later restoration. In addition to reducing CO2 emissions, the hybrid material embodies the circular economy principle of sustainable development by recycling waste seashells into concrete. This not only utilizes waste but also reduces the need for sand and limestone extraction, reducing waste and increasing resource efficiency. Additionally, biorock technology can protect and restore marine ecosystems, as limestone produced through electrolytic mineral accretion attracts the habitat of marine life, such as coral reefs. Apart from exploring new materials, this thesis also explores a new form of habitation - underwater construction, which offers a potential solution to sea level rise and land scarcity.

Delimitations

This thesis focuses on the possibility of integrating seashell concrete and biorock technology as load-bearing structural materials for underwater construction. The design site is set in a future area that will be flooded by seawater and many of the underwater conditions are unknown at the moment, so the scenario design of the site is more of a hypothetical scenario. Moreover, the experiments on the materials are more focused on small samples and are carried out in an aquarium simulation of the marine environment rather than in a real marine environment. In the material experiments, the material ratios and setups are based on the existing references and then the 'recipes' for the material experiments are created. Due to the time constraints of the thesis, it is hard to explore the effects of the material's long-term underwater conditions, such as corrosion, strength, etc.

Structure & Timeline




Design Proposal II
Prototype
Concept Development:
Program & Form
Exploration Phase III
Material Experiment:
Seashell Concrete
Biorock Technology
(Separate & Samples)
Evaluation Phase
Simulation in Grasshopper
Material Testing:
Physical Model for Material Experiment
Design Phase IV
Modification and Optimization according to the Evaluation Results
Draft Drawings
Final Review
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EVALUATION
DESIGN
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& Samples)
Design Proposal III
Concept Development:
Spatial Design
Structure & Detail
Exploration Phase IV
Material Experiment:
Seashell Concrete
Biorock Technology
(Hybrid Material Test)
Production Phase
Drawings
Animation Production
Representation for Final Review

Methods and Tools

The master's thesis is divided into 5 phases: research phase, experiment phase, finding phase, design proposal and evaluation phase. Each phase has a different focus and methodology and tools.

Research Phase

Artifact Analysis: The physical and chemical properties of many marine-based materials are studied. The possibilities and cases of using these marine materials for underwater construction are analyzed and organized to select the optimal materials for research.

Content Analysis: Different sources of information focusing on underwater living for humans, underwater construction, marine ecosystems, marine-based material, and energy efficiency beneath the water are analyzed, which can help get comprehensive knowledge for the design proposal.

Case Studies: The case studies of practical and conceptual projects on underwater architecture help to understand the current thinking of underwater architectural design, such as what materials and structures to use and what environmental challenges to deal with.

Literature Reviews: Conducting literature reviews provide the theoretical foundation for understanding previous research and advancements in marine biomaterials, underwater architecture, and sustainable design, helping to identify knowledge gaps and guide experimental and design phases.

Experiment Phase

The experimental phase is divided into four experiments, Experiment 1 - Traditional Concrete, Experiment 2 - Seashell Concrete, Experiment 3 - Biorock Technology and Experiment 4 - Hybrid Material Experiment. Each experiment has different methods and techniques.

Experiment 1 - Traditional Concrete: This experiment served as a control group to compare the properties of traditional concrete with those of the experimental materials, including compressive strength, durability, water absorption and so on.

Experiment 2 - Seashell Concrete: Waste shells were recovered and ground to different sized particles, some were used as aggregates for concrete and some were used as powder to be calcined at high temperatures to replace cement in the concrete and the concrete made with waste seashells was tested against the control concrete for strength and properties.

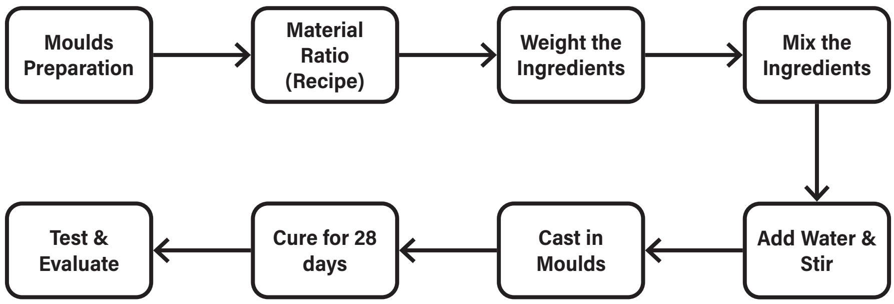
Experiment 3 - Biorock Technology: A metal wire mesh (cathode) and a metal rod (anode) submerged in seawater were connected with a low-voltage DC power supply, and mineral deposits(limestone/$CaCO_3$) were obtained on the metal wire mesh at the cathode through electrochemical reactions, and the growth rate and structural suitability were measured.

Experiment 4 - Hybrid Material: Combining seashell concrete and biorock technology, the seashell concrete is wrapped with a metal wire mesh and then submerged in seawater, connected to a low-voltage DC power supply, and this hybrid material is evaluated for strength, durability, and other properties.

Finding Phase

Evaluative Research: Evaluate and analyze the results of the material experiments to observe the difference in the performance of seashell concrete before and after incorporating biorock technology to determine if biorock technology can be used to improve the strength of seashell concrete for underwater construction.

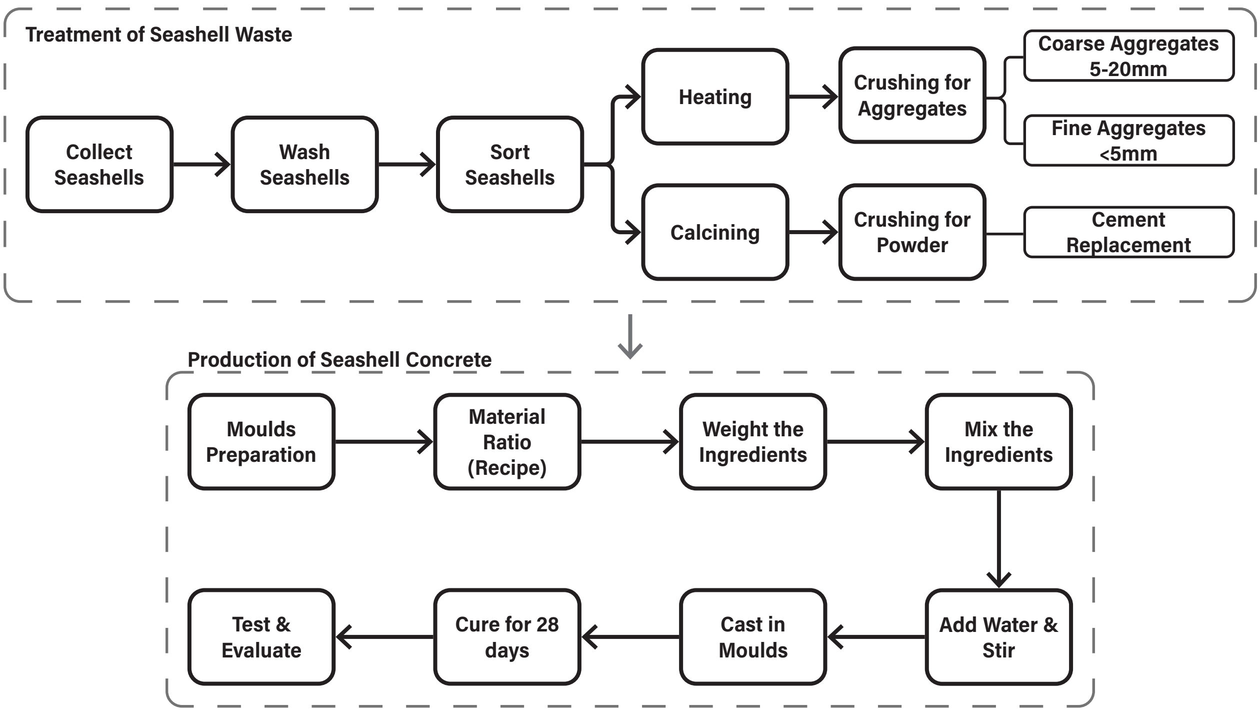
Experiment 1 - Traditional Concrete



Tools: brushes, coating(petroleum jell/wax/oil), moulds, mixing container, measuring cup 1000ml, measuring spoons, kitchen scale, trowel,stirring tool, sandpaper, masking tape, gloves, sieves.

Materials: cement (portland cement), coarse aggregates(gravel/ crushed stone), fine aggregates(sand), water, admixtures(acrylic paint).

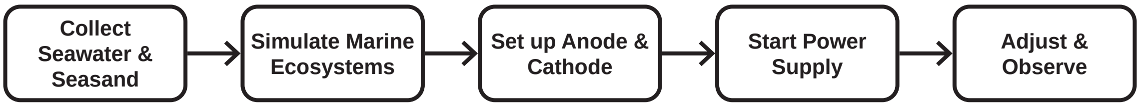
Experiment 2 - Seashell Concrete



Tools: brushes, coating(petroleum jell/wax/oil), moulds, mixing container, measuring cup 1000ml, measuring spoons, kitchen scale, mortel, tongs, trowel,stirring tool, sandpaper, masking tape, gloves, sieves, saucepan, oven, calcinaation equipment.

Materials: seashell powder, seashell fine aggregates, seashell coarse aggregates, clay, steel slag ash, gypsum, admixtures(acrylic paint).

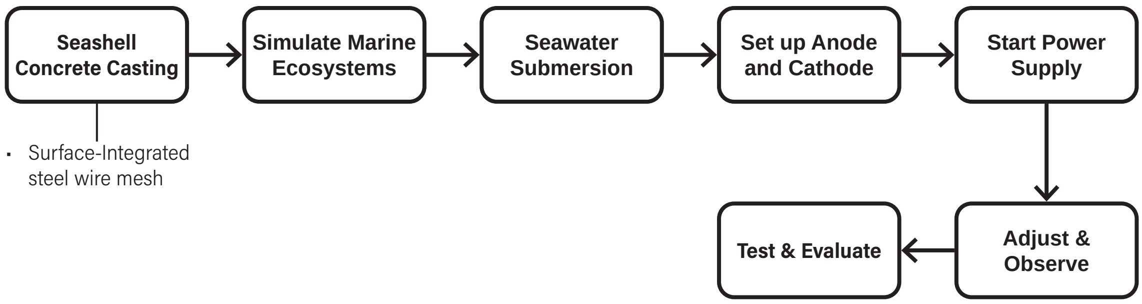
Experiment 3 - Biorock Technology



Tools: aquarium, DC power supplyment, thermostatic heater, small water pump, gloves, measuring cup 1000ml, masking tape

Materials: seawater, seasand, coral pro salt(RED SEA), metal rod(aluminum/ carbon), steel wire mesh, direct current(3-6V)

Experiment 4 - Hybrid Material



Seashell Concrete

Tools: brushes, coating(petroleum jell/wax/oil), moulds, mixing container, measuring cup 1000ml, measuring spoons, kitchen scale, mortel, tongs, trowel,stirring tool, sandpaper, masking tape, gloves, sieves, saucepan, oven, calcinaation equipment.

Materials: seashell powder, seashell fine aggregates, seashell coarse aggregates, clay, steel slag ash, gypsum, admixtures(acrylic paint).

Biorock Technology

Tools: aquarium, DC power supplyment, thermostatic heater, small water pump, gloves, measuring cup 1000ml, masking tape

Materials: seawater, seasand, coral pro salt(RED SEA), metal rod(aluminum/ carbon), steel wire mesh, direct current(3.5V)

Design Proposal

AI Generator: AI generators like Midjourney are used to get some inspiration for the design concept. Moreover, it can help create the images for the cover page or title page.

Scenarios: A scenario is created in a digital model using Blender to simulate the underwater world, including rocks, sand, etc., which can be useful to understand the surrounding of the design building.

Prototyping: Getting some inspiration from AI generators, some of the AI images are chosen to analyze and extract the elements for the design prototype. Then, the block combinations and shapes are created in Rhino, which are translated from the elements extracted before, from which the concept for the design can be progressed and optimized.

Rapid Iterative Testing & Evaluation: The prototype design was developed through multiple iterations of testing and improvement in Rhino and Grasshopper, and the strengths and weaknesses of the iterative model were quickly evaluated in terms of aesthetics, functionality, and performance data to optimise and improve the design.

Evaluation Phase

Simulation Exercises: First, check if the results match those in the material experiment phase or if the hybrid solutions are impoved by a physical model re-experimented with the material and structure. Secondly, the feasibility of the structure is evaluated using simulation software, like Grasshopper, to test whether the building can be supported under conditions of water pressure, water temperature, salinity, and so on.

Research Through Design

The methodology guided the development of the entire thesis by using design to explore the feasibility of seashell concrete and biorock technology as hybrid materials for underwater construction. The material experiments provided an understanding of the properties of seashell concrete and biorock technology and the potential of combining the two, and from the material experiments the optimum ratio of materials was found as a conclusion to be used in the later stages. In the design phase, an optimal structure was identified through the iterative process of prototyping and design, and then material experiments were conducted again with the structure to test whether it could be used as a load-bearing structure underwater.

LITERATURE REVIEWS

Seashell Concrete

Concrete

Concrete is one of the most commonly used building materials in modern construction, which is characterized by high strength, durability and plasticity, especially for underwater construction (Nichelson, B. J, 2023). Concrete, a conposite construction material, is made by cenment, aggregates and water, of which cement is the most essential and least sustainable material. The main reason for this is that cement is a manufactured product, where rocks are first mined, then transported to a cement manufacturing plant, then ground into a powder, mixed in specific proportions, and then calcined in a large kiln, where the raw materials react at high temperatures to produce calcium silicate(Nichelson, B. J, 2023), which is the main ingredient of Portland cement.

Cement

Cement acts as a binder in the process of concrete making, combining coarse aggregates (crushed stone) and fine aggregates (sand) that undergo several chemical reactions to harden and form a strong material. Portland cement is the most common type of cement, which consists of lime(CaO), silica(SiO_2), and alumina(Al_2O_3)(Nichelson, B. J, 2024). It is also a fine powder, formed by heating limestone($CaCO_3$) and clay minerals at high temperatures in a kiln to form clinker, to which about 5% gypsum is added and then ground(Wikipedia contributors, 2024). When a certain amount of water is added to this grey powder, the components in the powder will have a chemical reaction to form hydrated calcium silicate, which will create a hard material when it solidifies. This type of cement, which reacts with water or sets underwater, is called hydraulic cement(Nichelson, B. J, 2024).

Construction Aggregates

Construction aggregate, also commonly referred to as aggregate, is a collective term for particles of various sizes, from coarse to powder, including sand, limestone, gravel, crushed stone and so on. The process of getting aggregates releases large amounts of carbon emissions. For example, the rock first needs to be blasted at a mining site to obtain larger pieces, then transported to a processing plant for further crushing, and finally transported to a designated location(Haynes, C. D., 2023). Concrete components include coarse and fine aggregates, which can be used as reinforcement to enhance the strength of the hybrid material(Haynes, C. D., 2023).

Seashell

According to Wikipedia, seashells, also called shells, are the firm exterior of marine mollusks to protect its soft parts. As the exoskeleton of spine-less animals, seashells' main components are calcium carbonate($CaCO_3$) or chitin. It is easy to find empty seashells on beaches, which become seashell waste. In this large amount of shell trash, there are different types of shells, such as oysters, mussels, cockles, clams, scallops and periwinkles (Mo et al., 2018).

Treatment of Seashell Waste

According to Mo et al. (2018), a few steps need to be done before reusing the discarded seashells: washing, heating, calcining, and crushing to the desired size. Washing can help remove salt content. In order to obtain dry and sterile aggregates, it would be better to heat the seashell in an oven at a temperature of 105 ℃ to 110 ℃ . Calcining at a temperature of 650 ℃ to 850 ℃ can help those seashells used as substitutes for cement remove the water, decompose and react to get calcium oxide. Finally, the shells are ground according to the size requirements of the coarse and fine aggregates and powder.

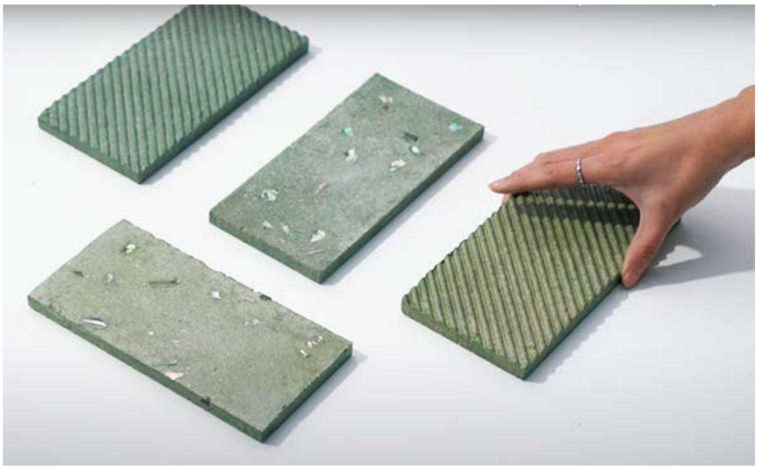
Seashell Concrete

According to Mo et al. (2018), seashell waste can be used as fine aggregates, coarse aggregates, and powder that can partially replace cement. Since the main component of discarded shells is calcium carbonate($CaCO_3$), similar to limestone, when calcined at high temperatures, the main element ($CaCO_3$) will decompose and react to produce calcium oxide(CaO) and carbon dioxide(CO_2). The lime(CaO) created during this process is one of the materials that make up cement. Different types of shells have various sizes and degrees of hardness. Grinding shells into different sizes of particles can be used as coarse and fine aggregates in concrete. When used as aggregates, oyster shells ground to less than 5 mm as fine aggregates where particles have similar fineness to ordinary sand, studied by Yang et al.(2010). Mussel and periwinkle shells can be used as coarse aggregates without crushing, with sizes between 16 and 25 mm, especially for those in plain concrete. However, because of its particle size and shape, the mechanical properties of seashell concrete, including compressive strength, flexural strength and so on, are lower than those of standard concrete. In the study of Mo et al. (2018), when making seashell concrete, seashells are used as aggregates and powders (cement substitute) in different proportions to replace those in standard concrete. The mechanical properties have different effects, some proportions can enhance the strength while others reduce the strength, so it is necessary to find an optimal ratio in order to make the seashell concrete meet the required strength requirements.

Moreover, they recommend that the concrete incorporated with seashells could be utilized for applications that do not require high strength, such as non-structural, decoration and insulation purposes. Newtab-22 also mentioned in their Sea Stone project that seashell concrete is not suitable for large-scale or projects with structural needs. Existing research on the use of seashell concrete for load-bearing structures still needs to be developed, so this master's thesis aims to explore the possibilities of seashell concrete in this aspect.

Photographed by the author









Material 'Sea Stone'

Newtab-22

The project is to create a concrete-like material using recycled waste shells by grinding them into aggregates and combining them with natural, non-toxic binders such as sugar and agar. According to Newrab-22, the material can be used as an alternative to concrete for decorative purposes and interior product designs such as vases, tiles, candle containers, etc. This is because the main component of shells is calcium carbonate, also known as limestone, which is also one of the main ingredients in making concrete. By using discarded shells to make concrete, it is possible to reduce some of the ore development. At the same time, the process of making sea stone is carried out manually, avoiding heat, electricity and chemical treatment, which is more environmentally friendly than the process of making concrete.

However, it is hard to use this alternative material for large or structural projects, and if it were to be used for large projects, an energy-intensive heating process would be required to give the material the strength of traditional concrete. Although the process is the same as that of cement, requiring high temperatures, the carbon dioxide emissions produced by making Sea Stone are less than those produced by making cement.

Photos Sources: Newtab-22. (2019-2020). https://www.newtab-22.com/%EB%B3%B5%EC%A0%9C-design-products

Biorock Technology

Biorock Technology

Biorock technology, also known as mineral accretion technology, was invented by architect Wolf Hilbertz in 1976 and allows the growth of materials for underwater construction. It is the electrodeposition of minerals in seawater, meaning that the cathode is connected to a metal wire mesh and the anode is connected to a conductive metal rod, such as carbon or magnesium alloy and by introducing a low current into the seawater, an electrolytic reaction is induced so that the wire mesh in the cathode grows the mineral deposition material(Hilbertz, W., 1979).This technology produces a material that is about three times stronger than traditional concrete and can grow over time(*Figure 3*), however, the material grows at a rate of 1-2 cm per year, which means it is time-consuming and costly to grow prefabricated construction materials such as roofs, walls, blocks, etc, as explained by Goreau, T. J. (2012).

Chemical Reaction

The nine main elements in seawater are chlorine, sodium, magnesium, sulphur, calcium, potassium, bromine, carbon, and strontium(Hilbertz, W., 1979). Thus, when a low electric current is introduced into seawater, these elements dissolve into ions and undergo a chemical reaction at the electrodes (*Figure 4*), producing chlorine gas(Cl_2) and oxygen(O_2) at the anode and hydrogen gas(H_2), calcium carbonate($CaCO_3$) and magnesium hydroxide($Mg(OH)_2$) at the cathode(Hilbertz, W., 1992). Hydrogen gas(H_2) can be stored and used as fuel. Calcium carbonate ($CaCO_3$) is the main component of limestone, which also attracts corals to grow and inhabit it, so that this mineral accretion method can restore coral reefs, especially those damaged areas(Hilbertz, W., 1976).

According to Goreau, T. J (2012), the chemical reactions are different when the voltage is in low and high conditions:

> *Under low voltage conditions, it is capable of generating calcium carbonate (limestone) precipitates at the cathode, and the main chemical reactions occurring at the cathode and anode are as follows:*
>
> ***Anode:***
>
> $$2H_2O = O_2\uparrow + 4H^+ + 4e^-$$
> $$H^+ + CaCO_3 = Ca^{2+} + HCO_3^-$$
>
> ***Cathode:***
>
> $$4H_2O + 4e^- = 2H_2\uparrow + 4OH^-$$
> $$Ca^{2+} + HCO_3^- + OH^- = CaCO_3\downarrow + H_2O$$
>
> *Under high voltage conditions, side reactions occur, such as an increase in the concentration of hydroxide ions, resulting in the generation of a magnesium hydroxide (brucite) precipitate at the cathode, and chlorine ions generating chlorine gas at the anode. The main chemical reactions that occur at the cathode and anode are as follows:*
>
> ***Anode:***
>
> $$2Cl- = Cl_2\uparrow + 2e^-$$
>
> ***Cathode:***
>
> $$Mg^{2+} + 2OH^- = Mg(OH)_2\downarrow$$
> $$Ca^{2+} + 2HCO_3^- = CaCO_3\downarrow + H_2O + CO_2\uparrow$$
>
> *More importantly, brucite(Mg(OH)2) can absorb carbon dioxide and be converted into magnesium carbonate($MgCO_3$), which is stronger than limestone(CaCO3).*
>
> $$Mg(OH)_2 + CO_2 = MgCO_3\downarrow + H_2O$$

As a Sink for Carbon Capture

According to Figure 4, Carbon dioxide(CO_2) is absorbed by seawater. When the low current passes through the seawater, it has a chemical reaction to form bicarbonate(HCO_3^-), which is then converted to carbonate(CO_3^{2-}) depending on the pH of the seawater(Hilbertz, W., 1992). Then, it combines with the calcium ions in the seawater to form calcium carbonate, which is the main component of limestone. Thus, the biorock technology can be used as a sink for carbon capture.

Self-repairing

This technology works through the electrodeposition of minerals that produce white limestone on the surface of the metal connected to the cathode, the hard rock coating grows thicker over time, thus protecting metals that are immersed in seawater for long periods of time from corrosion. According to Goreau, T. J. (2012), the mineral material grown by biorock technology makes it the only marine construction material that is self-repairing. For example, when the generated mineral layer breaks down, the damaged area starts the electrodeposition to form a new mineral layer. In addition, it can repair cracked reinforced concrete structures such as bridge piers so that the steel reinforcement inside does not corrode, and the limestone generated can fill in the cracked concrete sections.

Renewable Energy

The electricity required for the biorock technology process can be obtained from various forms of renewable energy sources, such as direct solar radiation, wave energy, tidal energy, tidal currents, temperature differential energy, salt differential energy, chemical reactions of marine organisms, etc.

Fig.3: Two years of Biorock material growing on iron bar.*(Source: Global Coral Reef Alliance. https://www.globalcoral.org/biorock-coral-reef-marine-habitat-restoration/)*

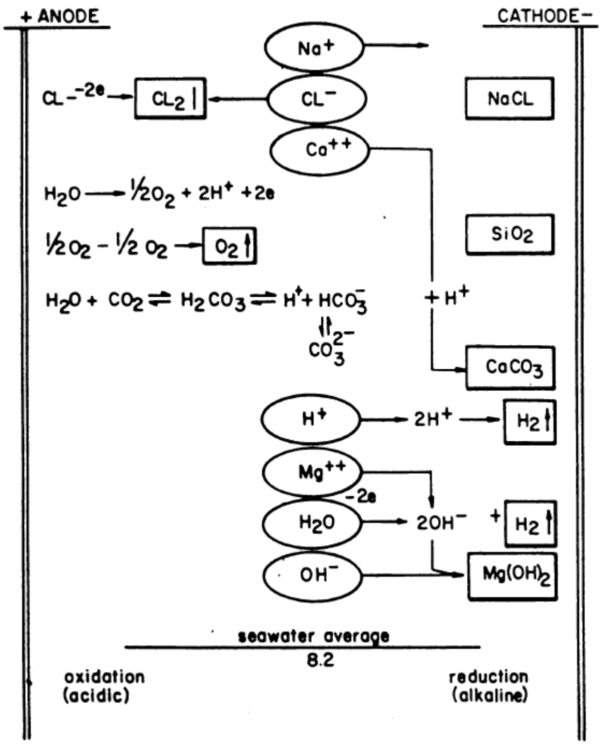


Fig.4: Chemical pathways of the mineral accretion process. *Hilbertz, W. (1992). Solar-generated building material from seawater as a sink for carbon. Ambio (Journal of the Human Environment, Research and Management).*

Pemuteran Coral Reef Restoration Project

Wolf Hilbertz & Tom Goreau, May 29 2001

The project is the world's largest biorock coral restoration project, 300 metres long and covering 2 hectares of land in the Pemudran Village Marine Reserve in northwest Bali, Indonesia. The coral reefs in Pemudran Village have suffered severe damage due to global climate problems and over-exploitation by people. Coral reefs are one of the most diverse ecosystems on the planet and are also known as marine rainforests (Mulhall, M, 2009). Therefore, there is an urgent need for action to restore coral reef habitats and the invention of biorock technology by Wolf Hilbertz offers great potential.

In 2001, 18 new structures were placed in the reserve, which are mainly made of construction rebar welded together and in various sizes and shapes. When a low-voltage electric current passes through, white limestone coating is generated on the surface of the reinforced structures, growing thicker over time to provide a habitat for coral transplantation, growth, and reproduction.

Based on preliminary observations reported in this project, many different species of corals grow on mineral deposits generated by biorock technology, for example, the Acropora colonies formed hundreds of new branches in less than a month and these corals generally have bright colour. Also, corals growing on mineral deposits have a low mortality rate and attract fish and other marine anurans such as sea urchins and starfish to thrive in the community, further enriching the ecosystem of the area.

"Coral-reef environments have among the highest rates of photosynthesis, nitrogen fixation, and $CaCO_3$ deposition of any environment, supporting larger numbers plant and animal species than any other marine habitat. Central to this high productivity is the unique biology of corals which is of vital importance to the reef community's structure, ecology, and nutrient cycle."

-- Wolf Hilbertz, (1992).

Photos Sources: Wolf Hilbertz. (2001). https://www.globalcoral.org/images/nggallery/album/pemuteran-bay-bali-indonesia-by-wolf-hilbertz

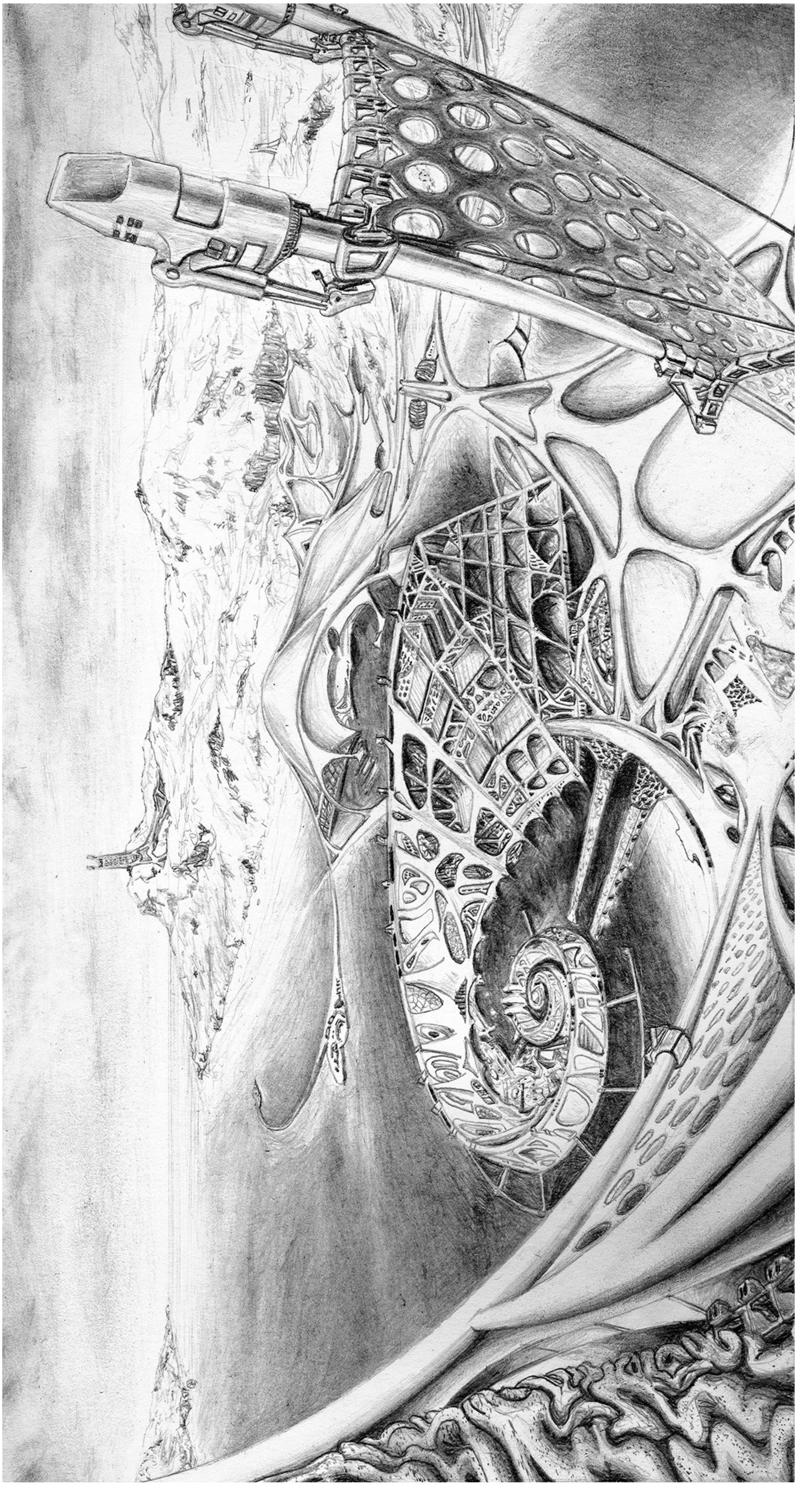


Fig.5: Perspective view of Autopia Ampere (after Newton Fallis) *by Paul Cureton, 2013, pencil and ink on paper.*

Autopia Ampere Project

Wolf Hilbertz & Newton Fallis, 1970

The project is a conceptual design for an unrealized marine eco-city. The design site is located in the Ampere Seamount, between the Madeira Islands and the tip of Portugal. The project is about using an electrodeposition reaction in the marine environment to grow a self-repairing marine city. The source of power required for this reaction is a low voltage DC power source generated by solar panels(Dobraszczyk, P., 2016). By applying a low-voltage electric current to the metal wire mesh immersed in seawater, various ions are released from the seawater, which in turn undergoes an electrochemical reaction on its surface, forming calcium carbonate deposits (Goreau, T. J, 2012). Over time, the deposits grow and can form limestone walls - a natural spiral dam that provides shelter for this conceptual city while adapting to changing ocean conditions (Dobraszczyk, P.,2017).

However, the conceptual design did not come to real due to the fact that the growth rate is 1-2 cm per year (Goreau, T. J, 2012), the time required to grow the thickness of the load-bearing walls for underwater construction would be pretty long, and also there are many extreme conditions that need to be overcome in order to live in a deep-sea environment for human beings, such as pressure, oxygen, and sunlight, etc.

MATERIAL EXPERIMENTS

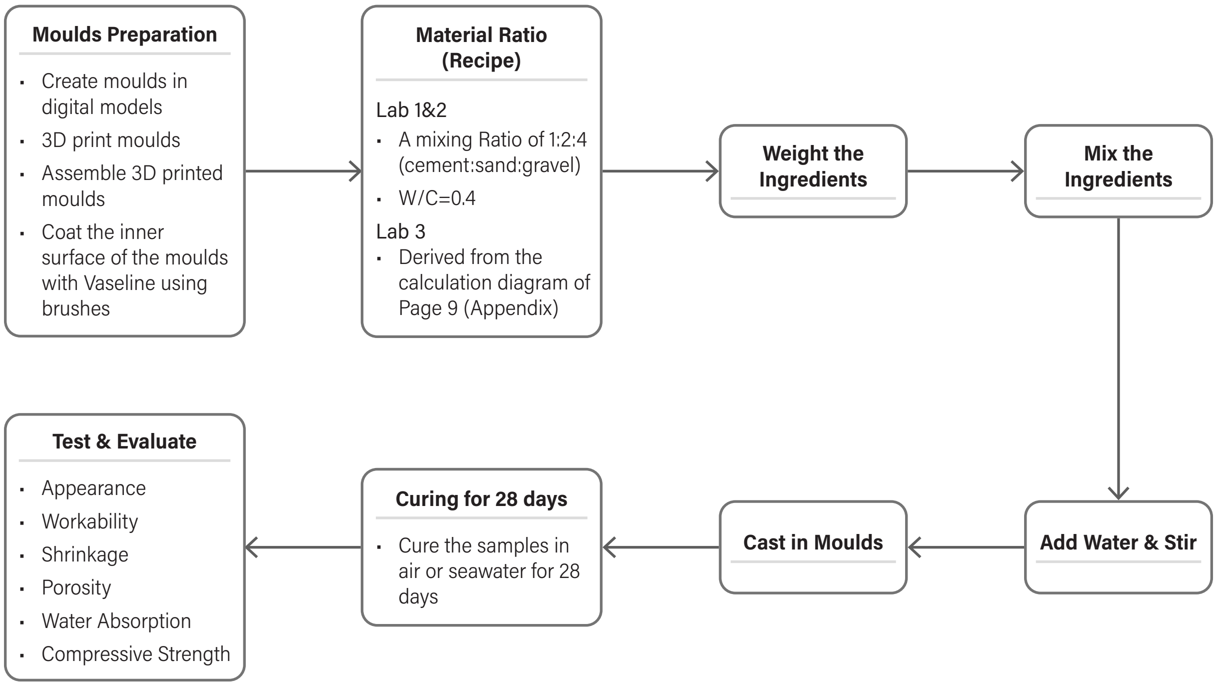
The purpose of material experiments is to answer the first two research questions:

- How can seashell waste be used as a sustainable alternative to traditional concrete?
- How can hybrid materials using seashell concrete and biorock technology be utilized for load-bearing structural purposes?

In parallel, it is also a chance to learn the properties of this hybrid material and observe how it grows and reacts, which will serve as a guideline for the form-finding and structure combination of the design proposal.

Experiment 1 - Traditional Concrete

Steps

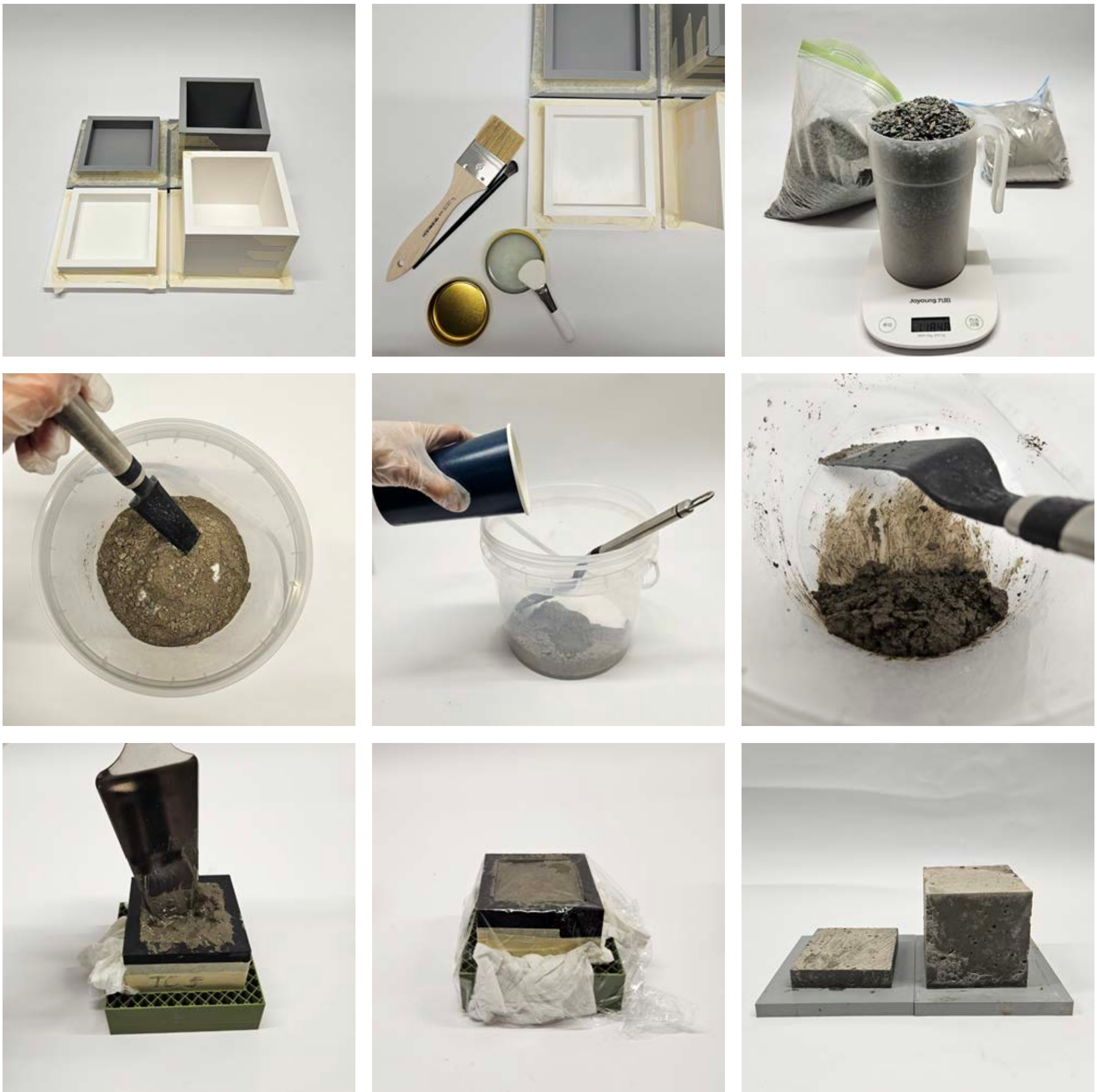


Ingredients Recipe

- Cement (Portland Cement)
- Coarse Aggregates: Gravel/ Crushed Stone
- Fine Aggregates: Sand
- Water
- Admixtures: Acrylic Paint

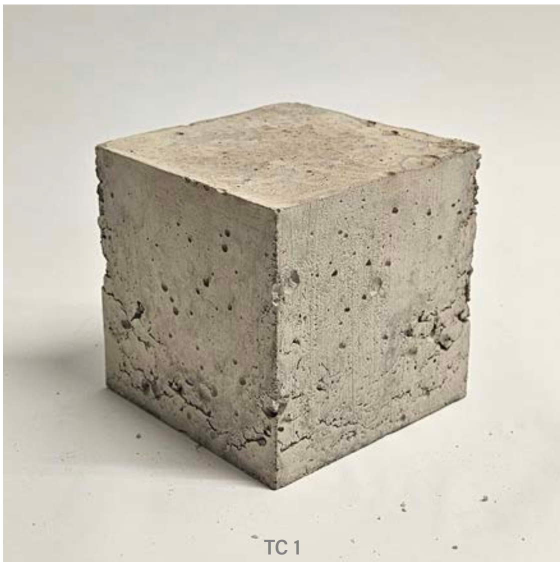
Lab	Mix Ratio	Sample	Shape	Dimension	Sand(g)	Gravel(g)	Cement (g)	W/C	Curing Area
Lab 1	1:2:4	TC1	Cube	10cm×10cm×10cm	685.71	1371.43	342.86	0.4	Air
		TC2	Tile	10cm×10cm×2cm	137.14	274.29	68.57		
Lab 2	1:2:4	TC3	Cube	5cm×5cm×5cm	85.71	171.43	42.86	0.4	Air
Lab 3	1:1.7:1.9	TC4	Cube	5cm×5cm×5cm	104.68	122.58	63.56	0.45	Air
		TC5							Seawater

NOTE: Detailed informations of the experiment process can be seen in Appendix P3-P10.



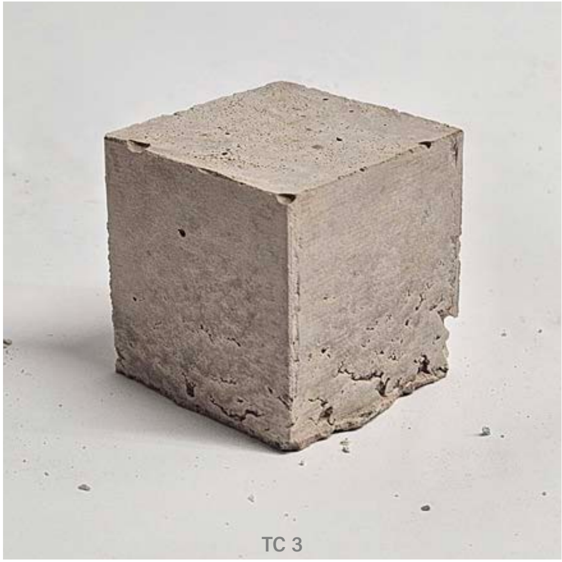
This experiment served as a control group to compare the properties of traditional concrete with those of the experimental materials(seashell concrete), including compressive strength, durability, water absorption and so on.

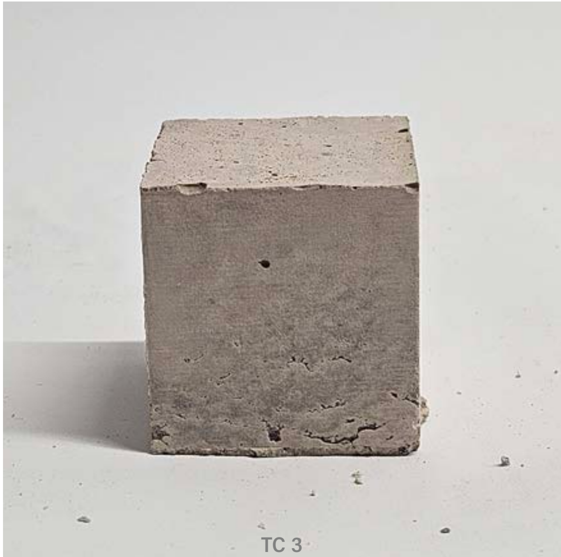
LAB 1


TC 1


TC 2

LAB 2


TC 3


TC 3

LAB 3

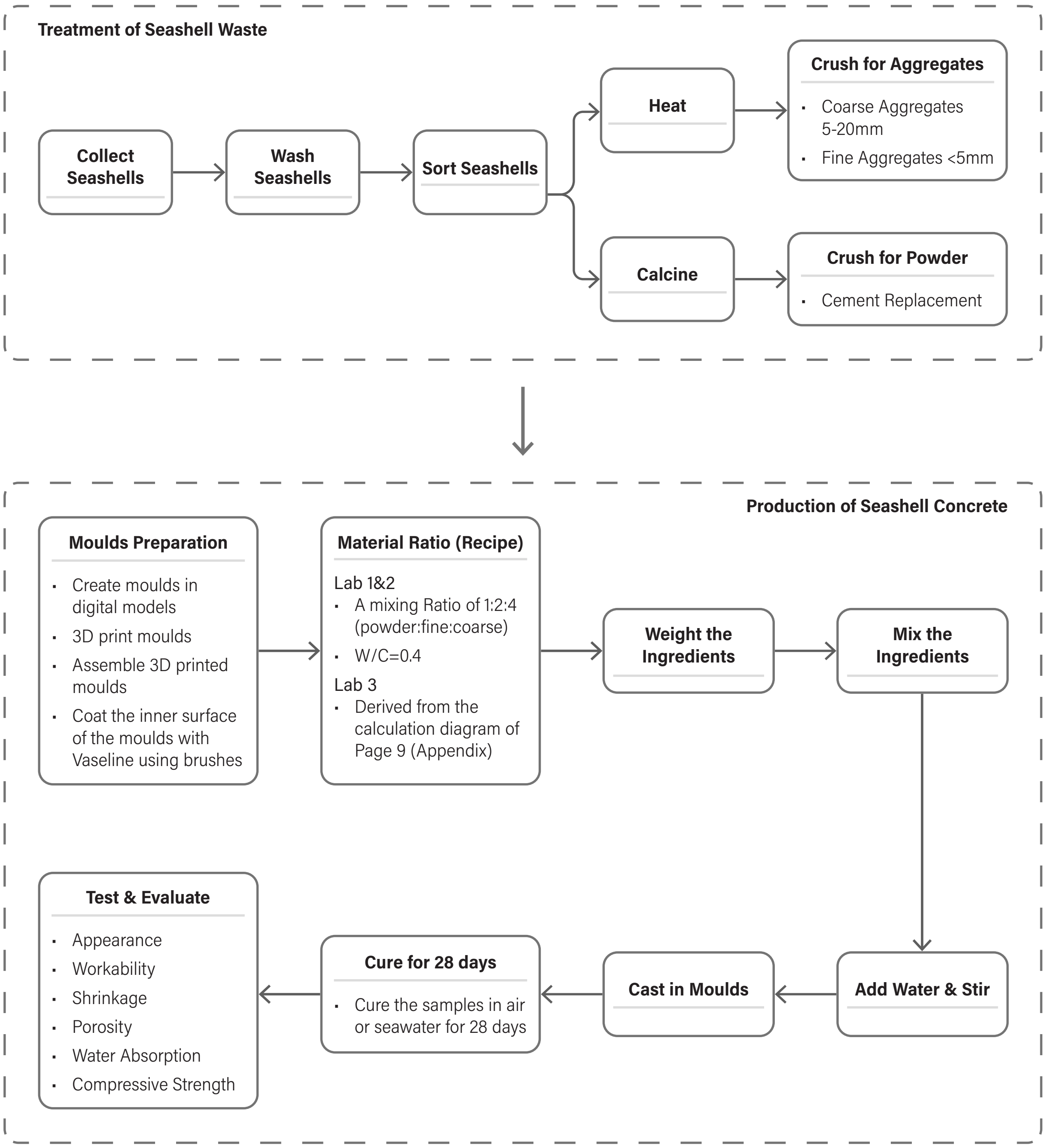

TC 4


TC 5

NOTE: Detailed data for sample comparisons and observations are provided in the Appendix P5-P8.

Experiment 2 - Seashell Concrete

Steps



NOTE: Detailed informations of the experiment process can be seen in Appendix P11-P22.







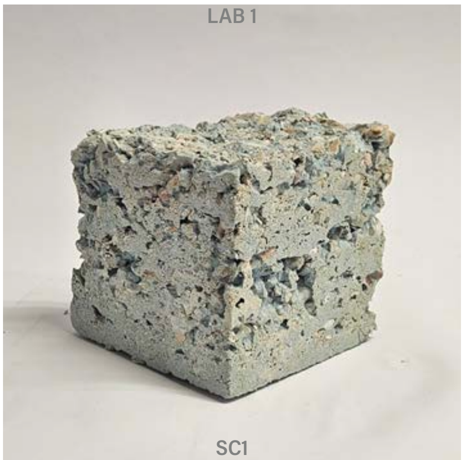


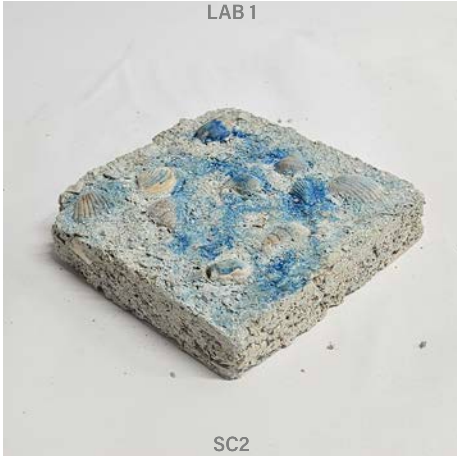


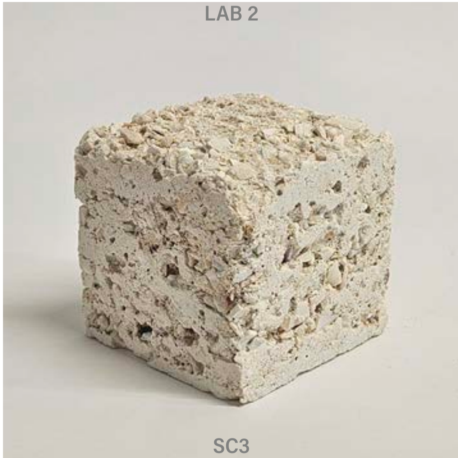

Ingredients Recipe

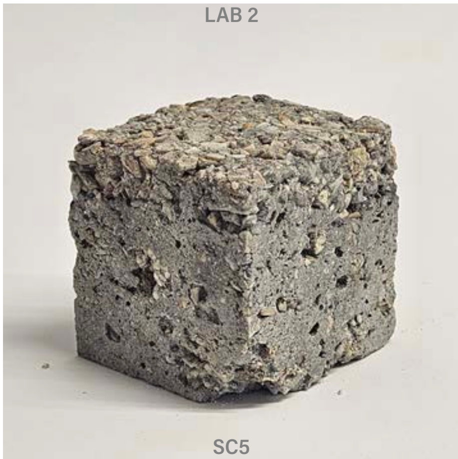
<table>
<tr><th>Lab</th><th>Sample</th><th>Dimension
(cm×cm×cm)</th><th>Fine Aggragates
(g)</th><th>Coarse Aggragates
(g)</th><th>Seashell Powder
(g)</th><th>Clay
(g)</th><th>Steel Slag Ash
(g)</th><th>Gypsum
(g)</th><th>W/SP</th><th>Curing Area</th></tr>
<tr><td rowspan="2">Lab 1</td><td>SC1</td><td>10×10×10</td><td>685.71</td><td>1371.43</td><td>342.86</td><td>0</td><td>0</td><td>0</td><td>0.4</td><td rowspan="2">Air</td></tr>
<tr><td>SC2</td><td>10×10×2</td><td>137.14</td><td>274.29</td><td>68.57</td><td>0</td><td>0</td><td>0</td><td>0.4</td></tr>
<tr><td colspan="11"></td></tr>
<tr><td rowspan="6">Lab 2</td><td>SC3</td><td rowspan="6">5×5×5</td><td>42.86</td><td>85.72</td><td>21.43
(100%)</td><td>0</td><td>0</td><td>0</td><td>0.85</td><td rowspan="6">Air</td></tr>
<tr><td>SC4</td><td>42.86</td><td>85.72</td><td>17.14
(80%)</td><td>4.29
(20%)</td><td>4.29
(20%)</td><td rowspan="5">1.07
(5%)</td><td rowspan="5">0.61</td></tr>
<tr><td>SC5</td><td>42.86</td><td>85.72</td><td>12.86
(60%)</td><td>7.50
(35%)</td><td>1.07
(5%)</td></tr>
<tr><td>SC6</td><td>42.86</td><td>85.72</td><td>12.86
(60%)</td><td>6.43
(30%)</td><td>2.15
(10%)</td></tr>
<tr><td>SC7</td><td>42.86</td><td>85.72</td><td>12.86
(60%)</td><td>4.29
(20%)</td><td>4.29
(20%)</td></tr>
<tr><td>SC8</td><td>42.86</td><td>85.72</td><td>17.14
(80%)</td><td>3.22
(15%)</td><td>1.07
(5%)</td></tr>
<tr><td colspan="11"></td></tr>
<tr><td rowspan="8">Lab 3</td><td>SC9</td><td rowspan="8">5×5×5</td><td>104.68</td><td>122.58</td><td>63.56
(100%)</td><td>0</td><td>0</td><td>0</td><td>0.91</td><td rowspan="8">Seawater</td></tr>
<tr><td>SC10</td><td>104.68</td><td>122.58</td><td>47.67
(75%)</td><td>12.72
(20%)</td><td>0</td><td rowspan="7">3.18
(5%)</td><td>0.78</td></tr>
<tr><td>SC11</td><td>104.68</td><td>122.58</td><td>41.32
(65%)</td><td>19.06
(30%)</td><td>0</td><td rowspan="6">0.86</td></tr>
<tr><td>SC12</td><td>104.68</td><td>122.58</td><td>41.32
(65%)</td><td>15.90
(25%)</td><td>3.18
(5%)</td></tr>
<tr><td>SC13</td><td>104.68</td><td>122.58</td><td>41.32
(65%)</td><td>12.72
(20%)</td><td>6.36
(10%)</td></tr>
<tr><td>SC14</td><td>104.68</td><td>122.58</td><td>41.32
(65%)</td><td>6.36
(10%)</td><td>12.72
(20%)</td></tr>
<tr><td>SC15</td><td>104.68</td><td>122.58</td><td>41.32
(65%)</td><td>3.18
(5%)</td><td>15.90
(25%)</td></tr>
<tr><td>SC16</td><td>104.68</td><td>122.58</td><td>47.67
(75%)</td><td>9.54
(15%)</td><td>3.18
(5%)</td></tr>
</table>

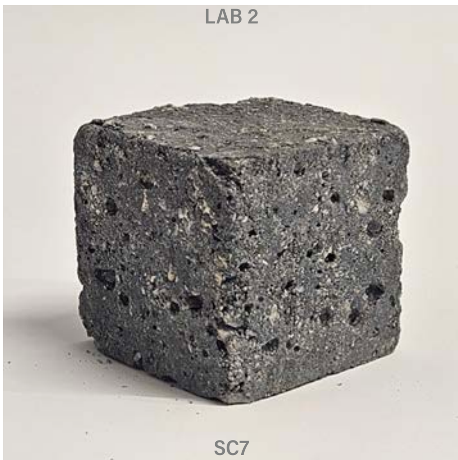
According to Wikipedia, cement consists of lime(CaO), silica(SiO2), and alumina(Al2O3), which is also a fine powder formed by heating limestone(CaCO3) and clay minerals at high temperatures in a kiln to form clinker, to which about 5% gypsum is added and ground. Therefore, admixtures such as clay, slag ash, and gypsum are mixed with seashell powder in different proportions to test the optimal seashell 'cement.'

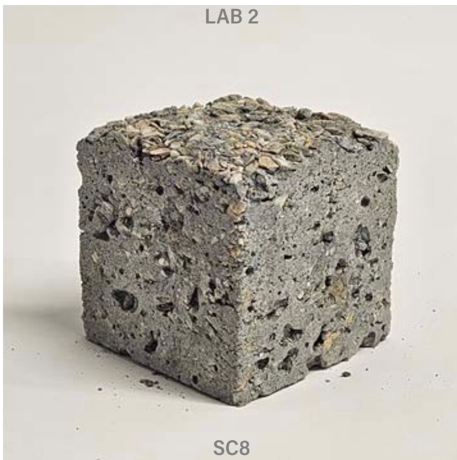




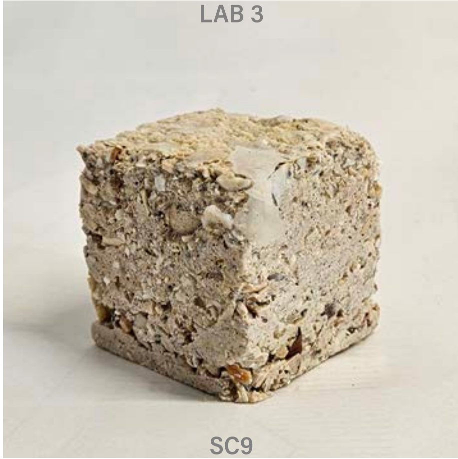




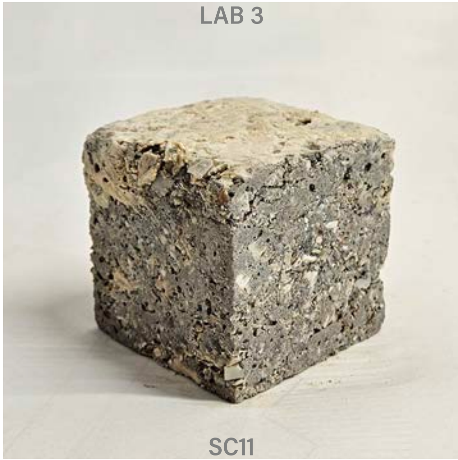


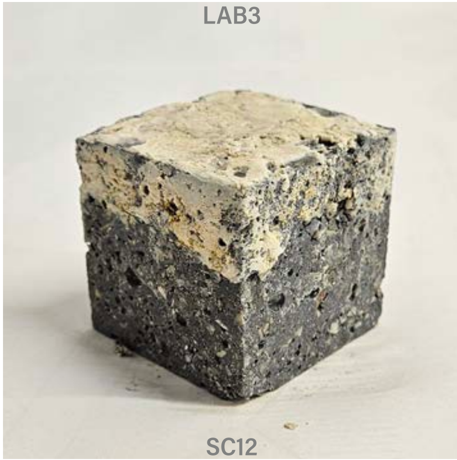


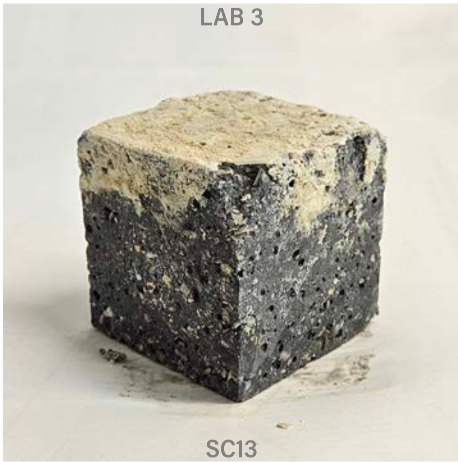
NOTE: Detailed data for sample comparisons and observations are provided in the Appendix P15-P22.

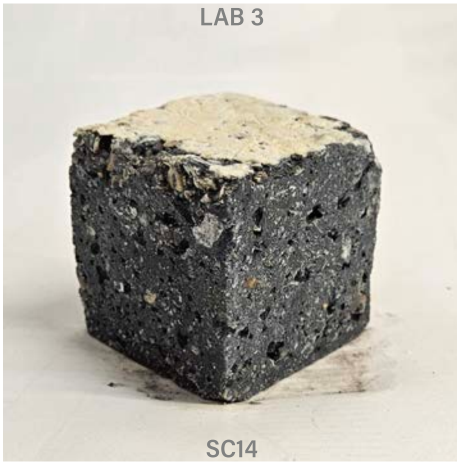

LAB 3
SC9

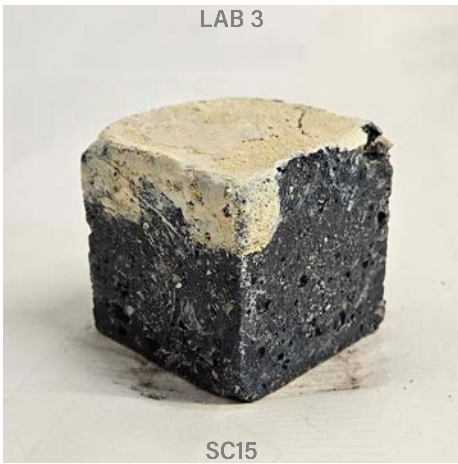

LAB 3
SC10

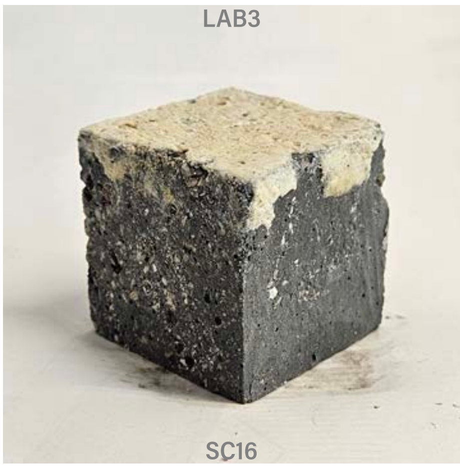

LAB 3
SC11


LAB3
SC12


LAB 3
SC13


LAB 3
SC14

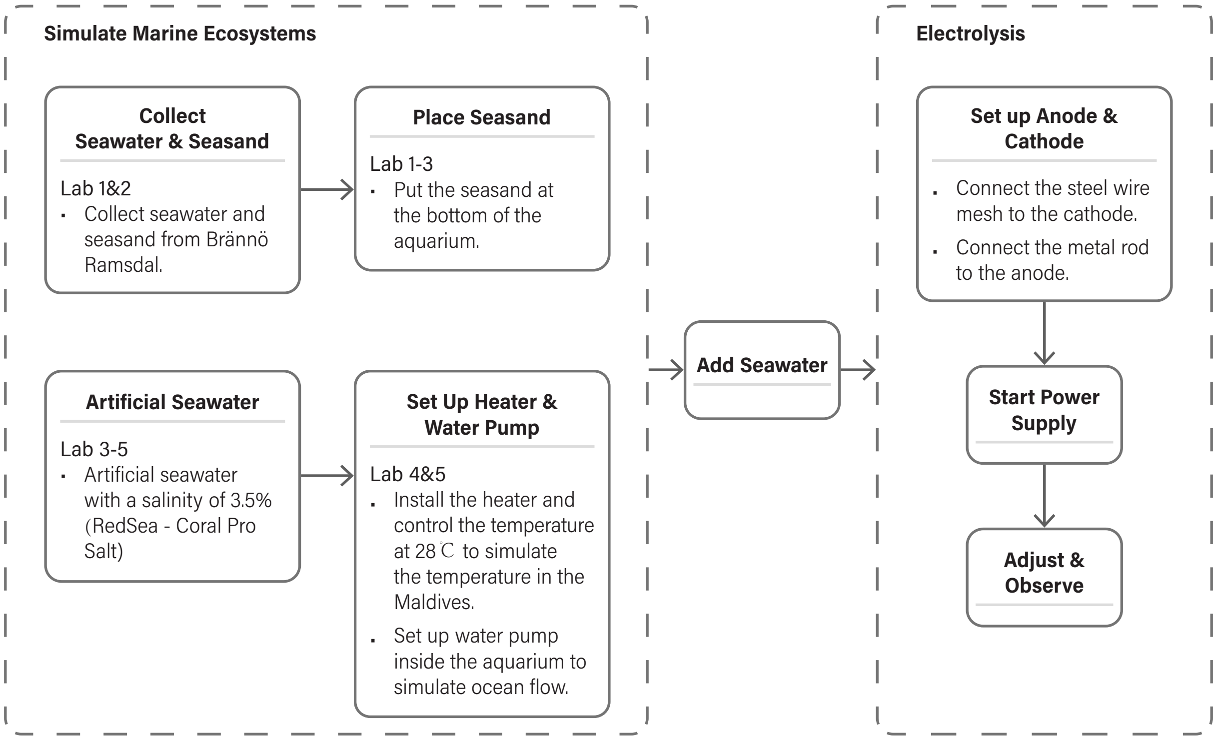

LAB 3
SC15


LAB3
SC16

NOTE: Detailed data for sample comparisons and observations are provided in the Appendix P15-P22.

Experiment 3 - Biorock Technology

Steps



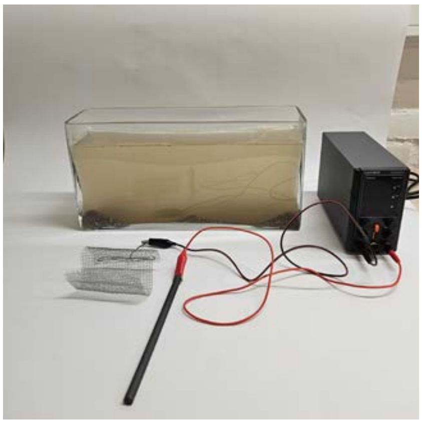
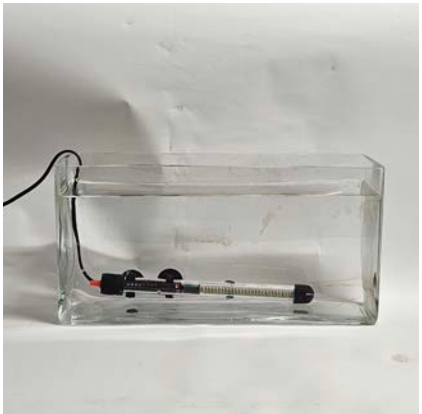
Recipe

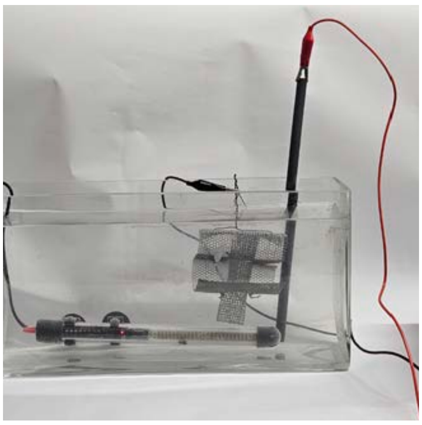
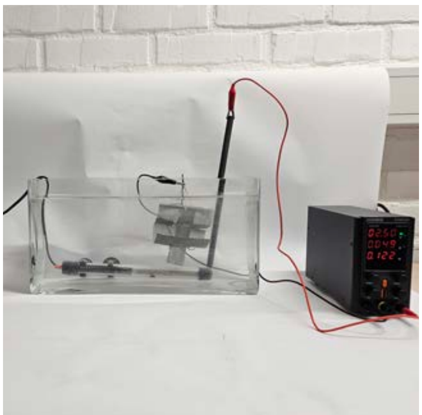
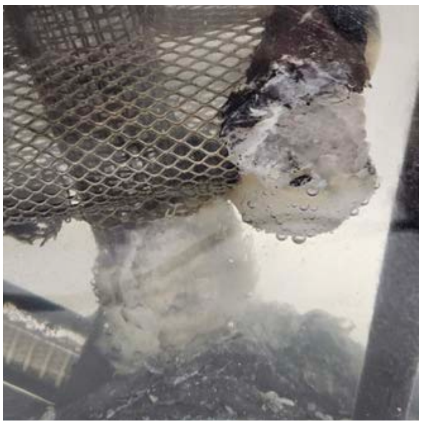
Lab	Sample	Steel Wire Mesh	Metal Rod		Seawater (L)	Direct Current		Time Use
		Dimension (cm×cm)	Type	Dimension (cm×mm)		Voltage (V)	Current (A)	Hour (h)
Lab 1	B1	12×12	Aluminium	20×12	5.3	6	0.50 - 2.00	72
Lab 2	B2	12×8.5	Aluminium	20×12	6.2	6	0.45 - 2.70	168
	B3	20×12						
Lab 3	B4	20×12	Carbon	20×10	6.2	3	0.092 - 0.119	168
Lab 4	B5	Complex Shape	Carbon	30×12	14.8(03.07)	3.5	0.231 - 1.4	672
Lab 5	B6	Cylinder (h:5cm Φ:4.5)	Carbon	30×12	6	3	0.53-0.92	168
	B7	Waisted Cylinder (h:5cm Φ:4.5)						

The seawater was initially set up at 5.3 litres, and additional seawater needed to be added to ensure enough ions to react during the electrolysis process. During the electrolysis process, the voltage was fixed while the currents changed every second, so the chart recorded the current value interval.

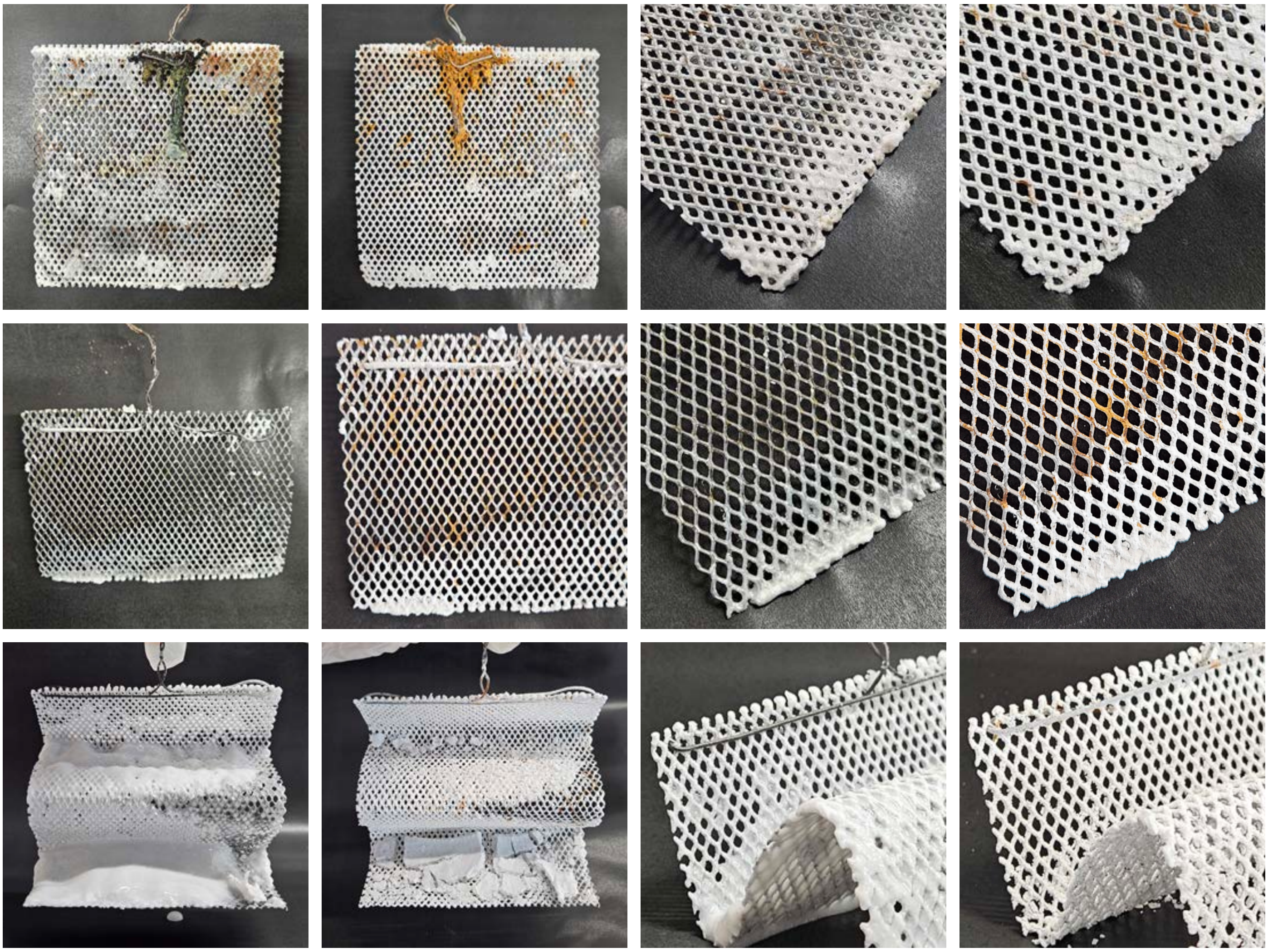
NOTE: Detailed informations of the experiment process can be seen in Appendix P23-P42.



During Lab 1 and Lab 2, the seawater was collected directly from the island, serving as the phase to know how this biorock grows and its properties. After determining the design site-the Maldives, the seawater was changed into artificial seawater with the aim of mimicking the seawater condition of the Maldives.

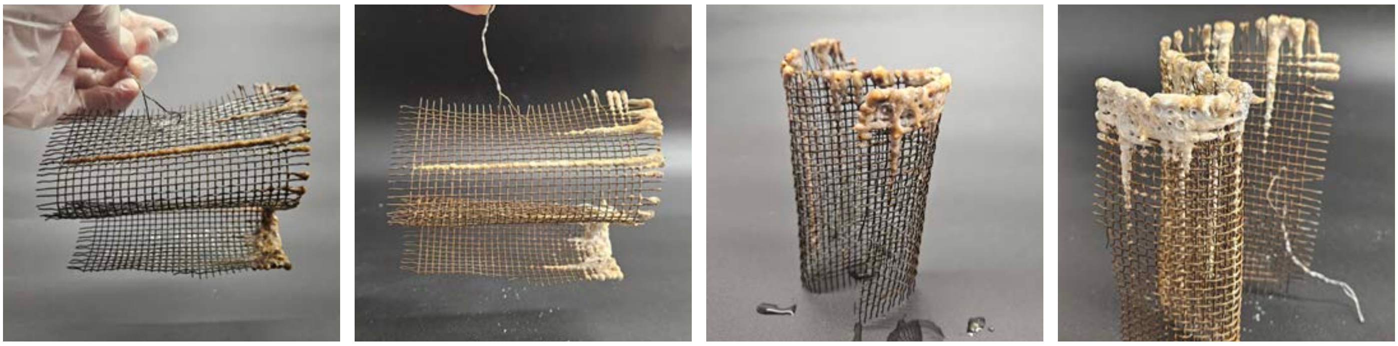


LAB 1 - B1

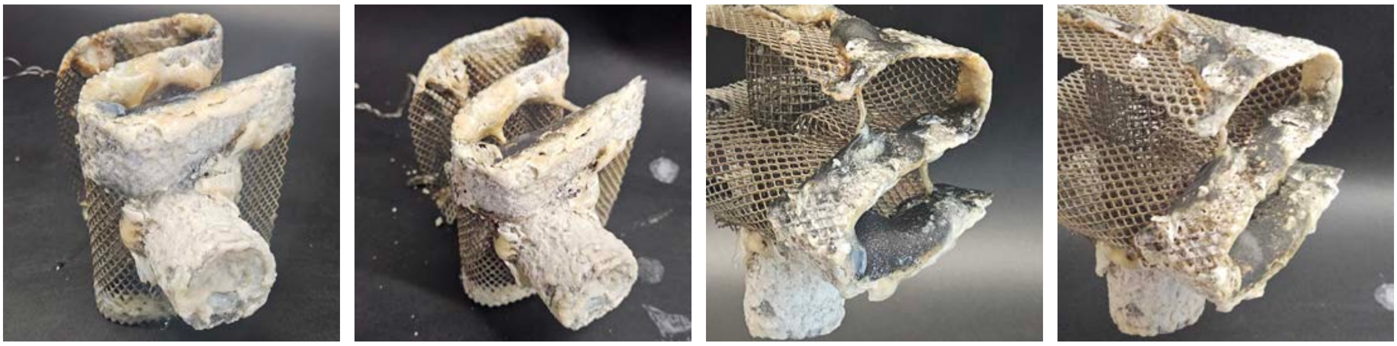
LAB 2 - B2

LAB 2 - B3

NOTE: Detailed data for sample comparisons and observations are provided in the Appendix P25-P30.



LAB 3 - B4



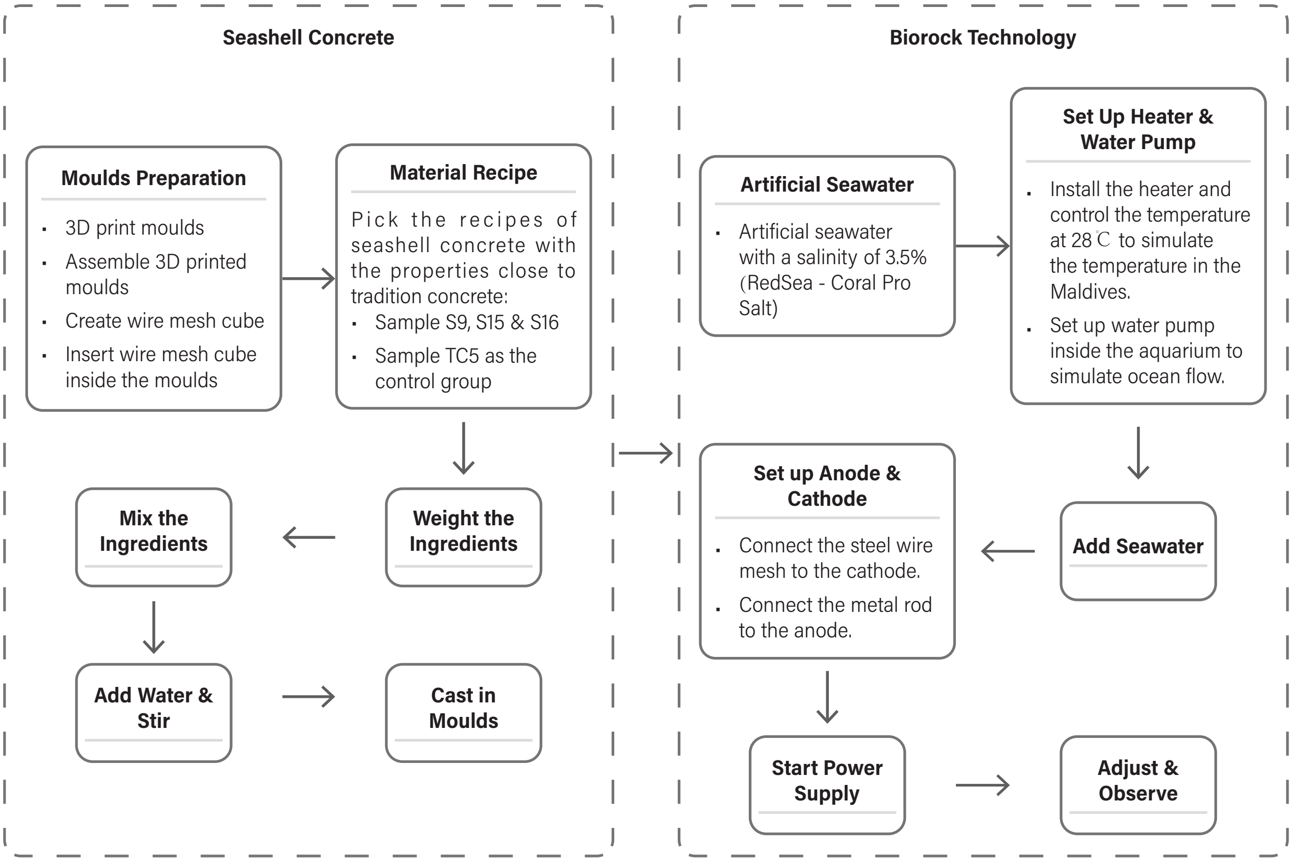
LAB 4 - B5

LAB 5 - B6 & B7

NOTE: Detailed data for sample comparisons and observations are provided in the Appendix P31-P38.

Experiment 4 - Hybrid Material

Steps

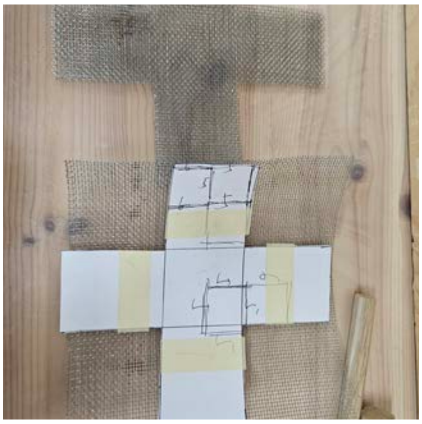


Recipe

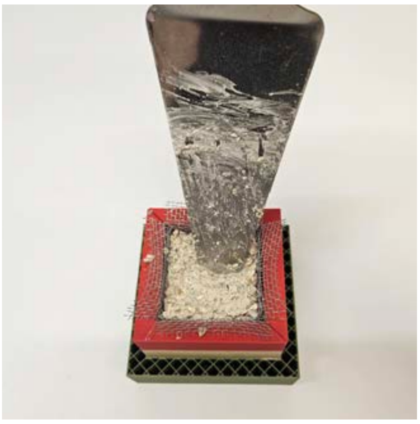
<table>
<tr><th rowspan="2">Lab</th><th rowspan="2">Sample</th><th rowspan="2">Size (cm×cm)</th><th rowspan="2">Fine Aggragates (g)</th><th rowspan="2">Coarse Aggragates (g)</th><th rowspan="2">Seashell Powder (g)</th><th rowspan="2">Clay (g)</th><th rowspan="2">Steel Slag Ash (g)</th><th rowspan="2">Gypsum (g)</th><th rowspan="2">W/SP</th><th colspan="2">Metal Rod</th><th>Time Use</th><th>Direct Current</th></tr>
<tr><th>Type</th><th>Size (cm×mm)</th><th>Hour (h)</th><th>Voltage (V)</th></tr>
<tr><td rowspan="4">Lab 1</td><td>H1</td><td rowspan="4">5×5×5</td><td>104.68</td><td>122.58</td><td>63.56</td><td>0</td><td>0</td><td>0</td><td rowspan="4">0.86</td><td rowspan="4">Carbon</td><td rowspan="4">30×12</td><td rowspan="4">672</td><td rowspan="4">3.5</td></tr>
<tr><td>H2</td><td>104.68</td><td>122.58</td><td>63.56 (100%)</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td>H3</td><td>104.68</td><td>122.58</td><td>41.32 (65%)</td><td>3.18 (5%)</td><td>15.90 (25%)</td><td rowspan="2">3.18 (5%)</td></tr>
<tr><td>H4</td><td>104.68</td><td>122.58</td><td>47.67 (75%)</td><td>9.54 (15%)</td><td>3.18 (5%)</td></tr>
</table>

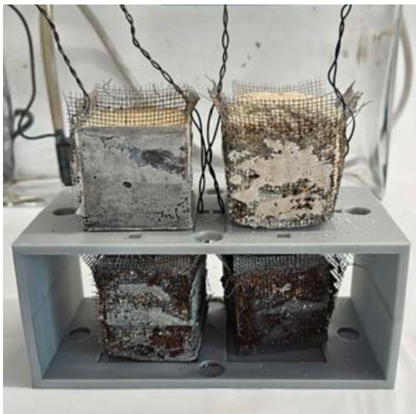
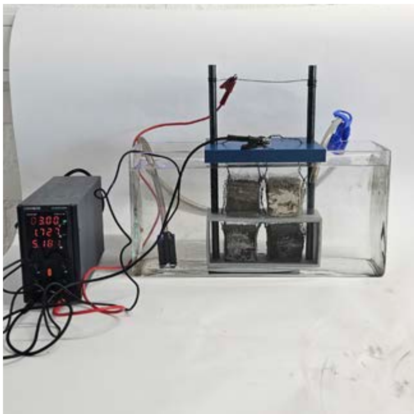
The recipe for H1 is from TC5, H2 is from SC9, H3 is from SC15, and H4 is from SC16. Because of the time limitation, the hybrid material lab only has one, so if the time is enough, it would be better to explore more based on the findings from lab 1.

NOTE: Detailed informations of the experiment process can be seen in Appendix P43-P48.







In order to grow even white materials, it was supposed to test the samples individually and place a carbon rod on each side of the seashell concrete sample. However, all the samples were experimented on simultaneously, and the amount of carbon rods was less due to the time limitation and the insufficient equipment.

Cured Sample | **Dry Sample**

HM1

HM2

NOTE: Detailed data for sample comparisons and observations are provided in the Appendix P45-P48.

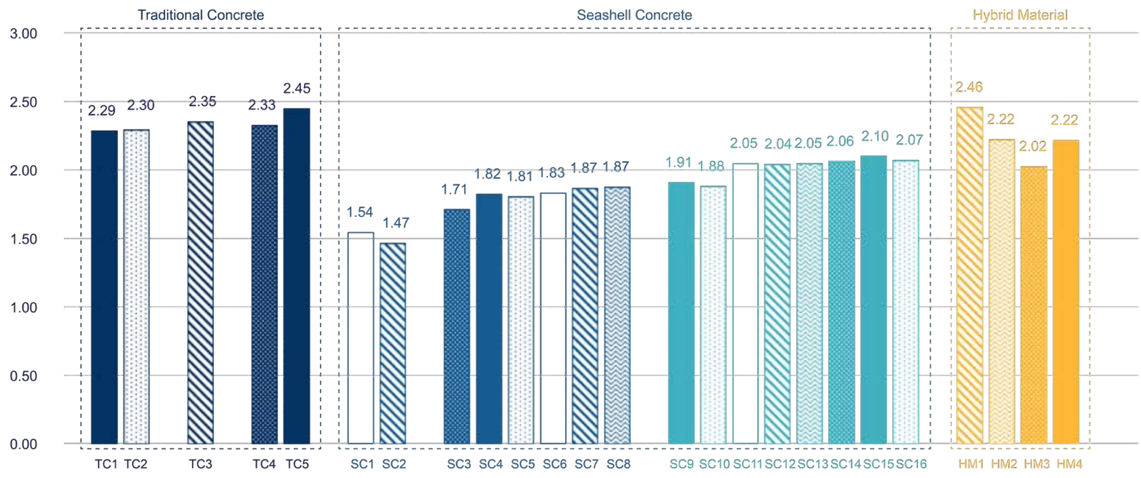
Cured Sample | **Dry Sample**

HM3

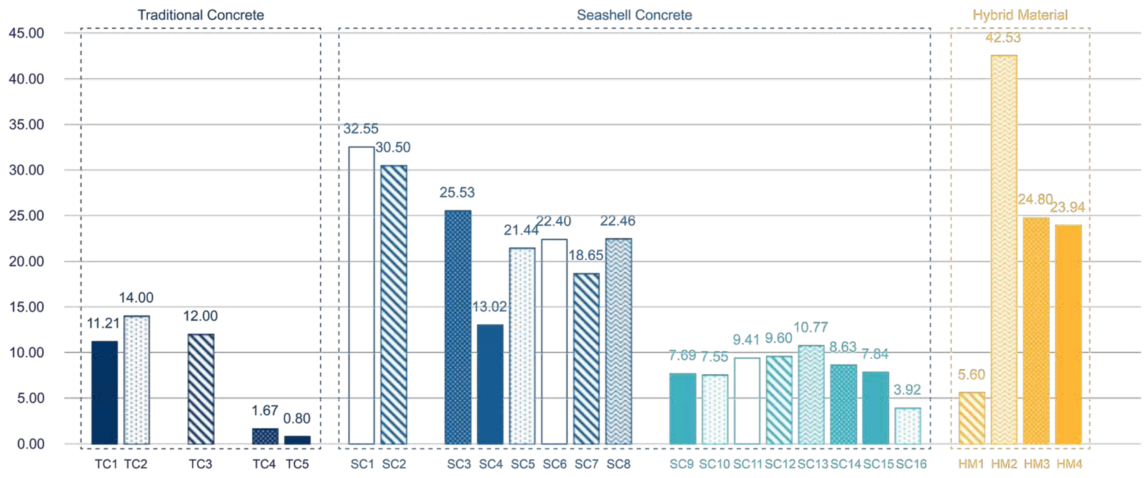
HM4

NOTE: Detailed data for sample comparisons and observations are provided in the Appendix P45-P48.

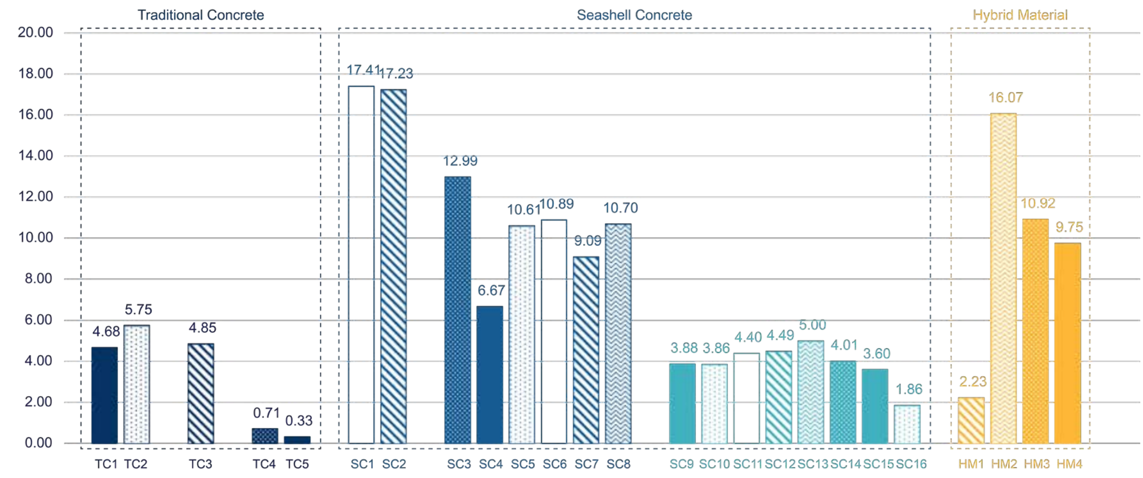
Evaluation



Density (g/cm^3)



Porosity (%)



Water Absorption (%)

Findings

The material experiments provided important information about the properties and limitations of seashell concrete, biorock technology, and their combinations. The first two research questions can be answered by observing all the experiments.

- ***How can seashell waste be used as a sustainable alternative to traditional concrete?***

  Seashell waste can replace cements and aggregates through proper treatments such as washing, grinding, and calcination. The experiment shows that seashell powder can bind the seashell aggregates and produce solid samples. However, some particles on the surfaces of these samples will fall off when touched. Moreover, their surfaces' textures all have voids and cracks and are not as smooth as those made by traditional concrete.

  The data comparison chart shown on the left shows that all the samples made with seashell concrete perform lower than traditional concrete, for example, with higher porosity and water absorption, as well as lower density and compressive strength. Even though some samples have been used with additives like clay, gypsum and steel slag ash to optimize the seashell concrete, they all presented worse than traditional concrete. Therefore, seashell concrete cannot be used for load-bearing applications. Instead, it can be used for decorative and non-load-bearing purposes.

- ***How can hybrid materials using seashell concrete and biorock technology be utilized for load-bearing structural purposes?***

  The Hybrid Material experiment shows that the wire mesh attached to seashell concrete surfaces grows white substances (limestone) after submerging in seawater with low-voltage electrolysis. However, this experiment only showed one side of the seashell concrete that was fully covered by the growing limestone because of a lack of time and equipment. It can be speculated that the growing limestone through seawater electrolysis can coat an extra solid layer, reducing water penetration and sealing voids and cracks on the surface of the seashell concrete. This limestone layer, called biorock, can be three times stronger than traditional concrete (Goreau, T. J, 2012). Moreover, using this biorock technology can attract coral to inhabit, and after they die, their body will transform into calcium carbonate, which is also the main component of limestone. Therefore, in theory, this hybrid material system can be used in load-bearing applications for underwater structures.

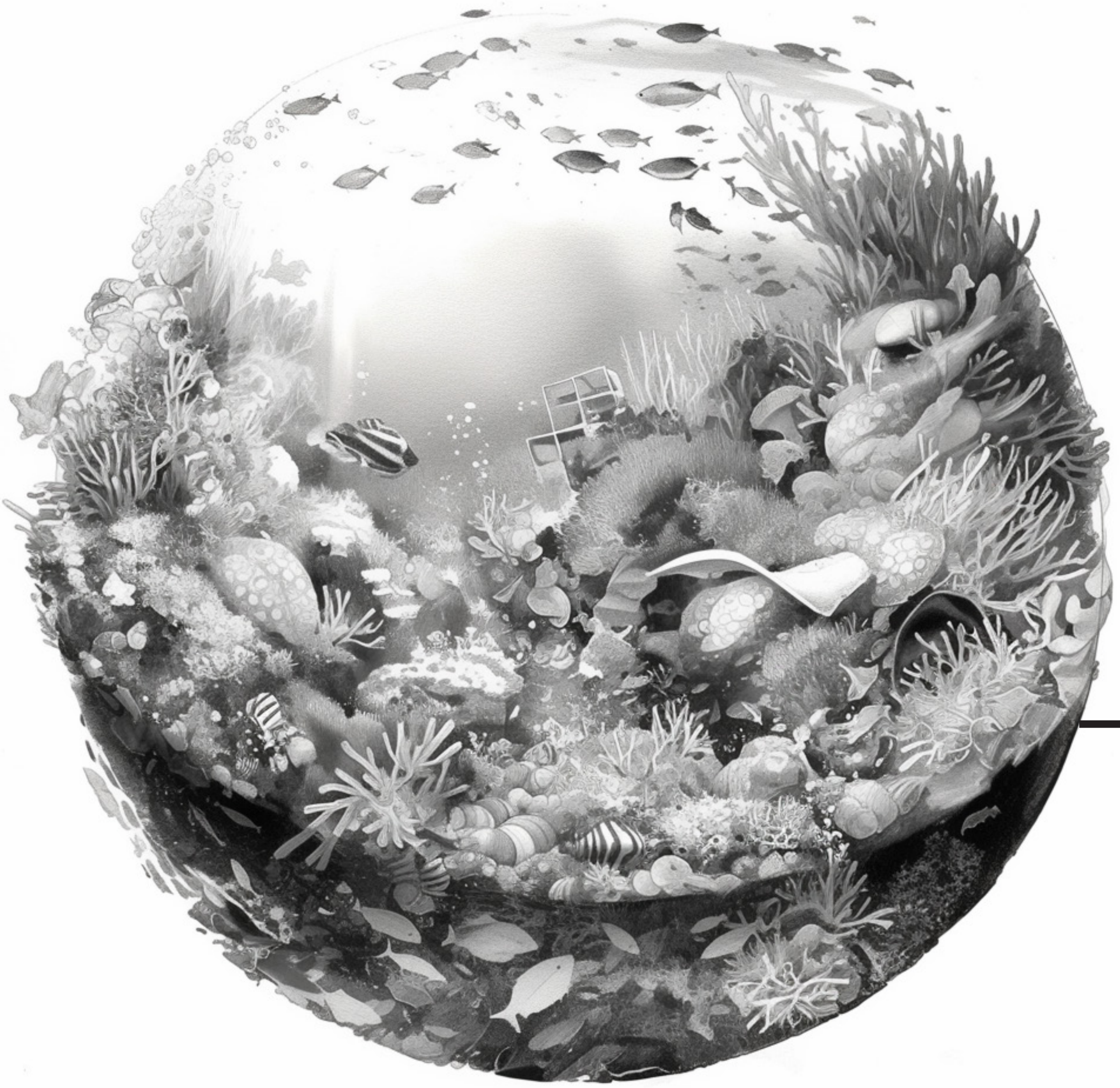
  Another interesting point is that this growing mineral layer can serve as the protective coat for the rusted steel framework. This means that biorock technology offers a self-repairing quality for the damaged rebar while accumulating more and more minerals under continued electrolysis. This process also protects the seashell concrete and makes their hybrid combination more suitable for underwater conditions, especially in places with severe corrosion and pressure.

- ***How can the growth pattern of biorock technology be used as a design strategy to guide the form-finding and structural composition in the design proposal phase?***

  The growth pattern of biorock in the electrolysis experiment shows that the places close to the metal rods (anode) have more mineral accretion. This suggests that a radial form, with a metal rod inserted at the centre, can grow more limestone more evenly. During the hybrid material lab, the steel wire mesh attached to seashell concrete grew more limestone than the steel wire mesh alone. However, mineral accretion only happened in the wire mesh exposed to seawater, the mesh embedded inside the seashell concrete did not contribute to mineral growth. Additionally, the mineral accretion process is time-based with the growing efficiency of 1-2cm per year, indicating that it will require a long time to achieve sufficient thickness and strength for the load-bearing wall.

  As a result, this hybrid system enables seashell concrete and biorock to work together, each compensating for the other's weaknesses. Suppose underwater buildings using this hybrid material want to be constructed quickly. One potential strategy is to cast the seashell concrete first, embedding steel wire mesh on the surface or inside as reinforcement. As the seashell concrete dissolves over time in the seawater, the exposed mesh starts the electolysis to grow biorock, enhancing the strength of seashell concrete and protecting the steel. In this approach, the building surface will have the smoother texture of seashell concrete.

  Another strategy is to grow biorock first on the exposed steel framework through mineral accretion, followed by the decoration with seashell concrete. In this case, the building's surface will show the rough and organic texture of biorock, and the places with the seashell concrete will be smoother.



SCAN ME

The architectural animation can be viewed through this QR code or the link below:
https://youtu.be/h1h4qkXeaSE

DESIGN PROPOSAL

The purpose of design proposal is to test and answer the last research question:

- How can an underwater building be constructed by using this hybrid material combining seashell concrete and biorock technology?

Site

Dhangethi Jetty, South Ari Atoll, Maldives

Maldives

The Maldives, consisting of 1192 coral islands organized in 25 atolls, is an archipelago in the Indian Ocean. More importantly, it has the lowest sea level in the world, with a maximum natural ground level of only 2.4 m and most of its land area averaging only 1.5 m. Also, more than 80% of the land consists of coral islands, all less than 1 metre high. As a result, the Maldives will likely be the first country in the world to be flooded by seawater due to the impacts of global warming and severe environmental problems such as rising sea levels (Wikipedia contributors, 2025).

Situated near the equator, the Maldives has a tropical monsoon climate, with temperatures remaining between 24 - 31°C throughout the year. These warm temperatures help corals thrive and speed up the production of calcium carbonate(limestone) through biorock technology (Korchef & Touaibi, 2020).

South Ari Atoll

The design site - Dhangethi Jetty - is located at Ari Atoll, which is a typical atoll that surrounds a lagoon. The formation of this topography can be divided into four main phases (Roger Williams University, n.d.):

- **Volcanic Subsidence:** As the volcano cools, the base of the volcano begins to sink, creating space for coral to grow.
- **Coral Reefs Growth:** Corals grow on the edge of the volcano, further generating the fringing reefs.
- **Barrier Reef:** Volcanic islands continue to descend and erode, while corals grow vertically upwards, forming a barrier reef.
- **Atoll Formation:** As the volcanic island continues to descend and the sea level continues to rise, the island is submerged below sea level, while the coral reefs along its edge continue to deposit and grow, eventually forming an atoll around the central lagoon.

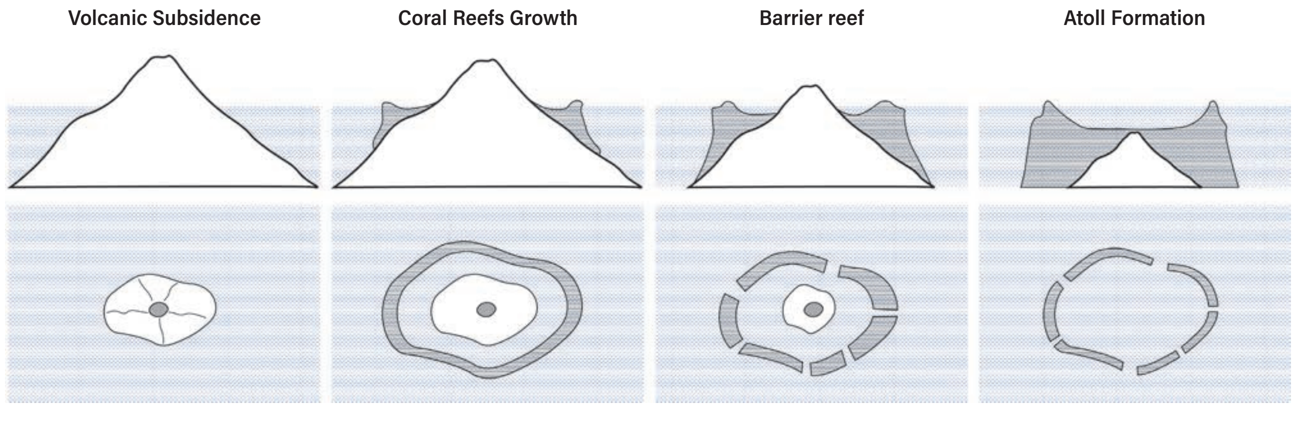
Dhangethi Jetty

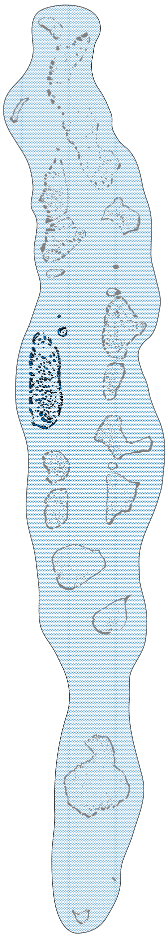
Located southeast of Ari Atoll, Dhangethi's topography is not atoll. Instead, it is an island developed by sediment produced by corals. Initially, corals grow and colonize the surface of the reef and, with ocean currents, continuously transport their sediments into the reef, accumulating sediments. Over time, the dead coral bodies produce calcium carbonate - a limestone-like substance- and new corals continue to grow on top of them, adding to this sediment and eventually contributing to the higher ridges that form the islands (Kench et al., 2020).

The waters around Dhangethi are home to vibrant coral reefs and diverse marine life, which makes it an ideal location for both tourism and coral research.

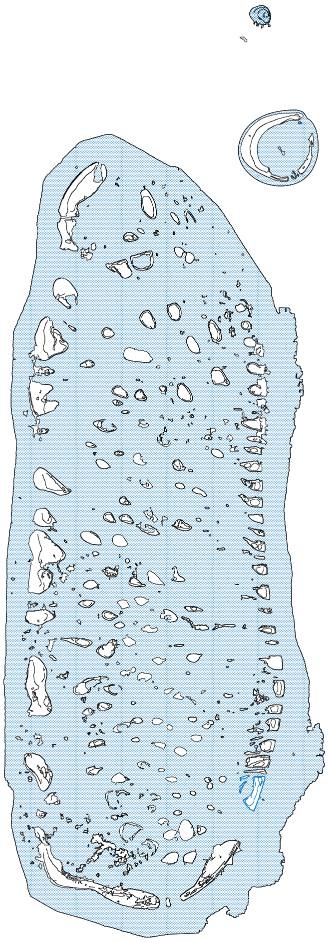
Coral Reef

From the formation of the site's topography, it is clear that corals are particularly important to the site. As one of the most diverse ecosystems on the planet, coral reefs provide habitats for many marine organisms. Moreover, when symbiotic with wormwood algae, this system can absorb carbon dioxide (Hilbertz, W. H, 1992). However, corals bleach, and extensive coral groups are dying out due to global warming and human over-exploitation. Without these, corals not only affect the atolls that support them - lacking the sediments that stabilize island topography - but also destroy marine ecosystems. Therefore, the restoration and resilience of coral reefs are of vital importance (Bessell-Browne et al., 2021).

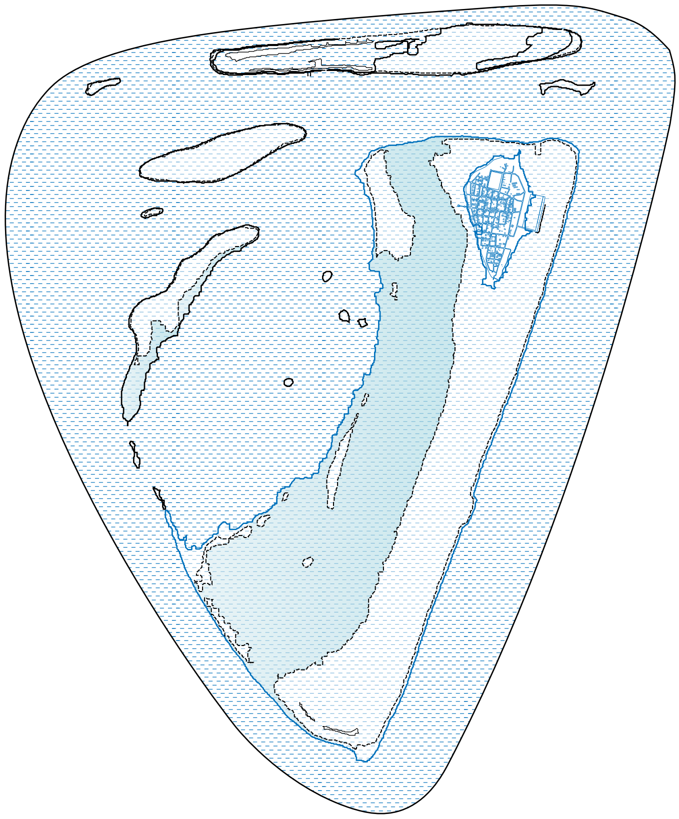




Maldives

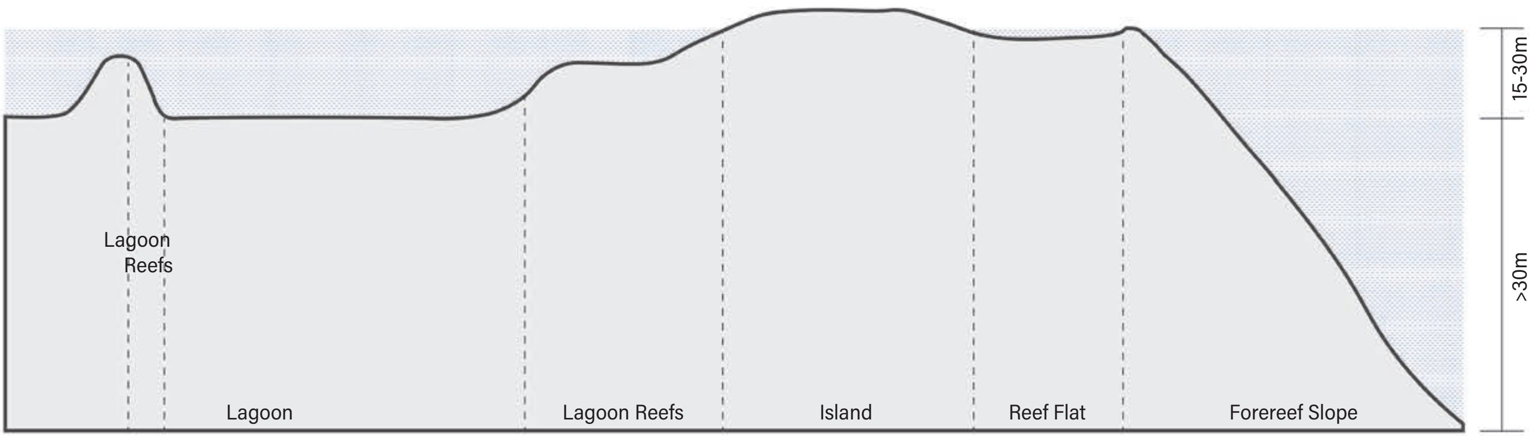


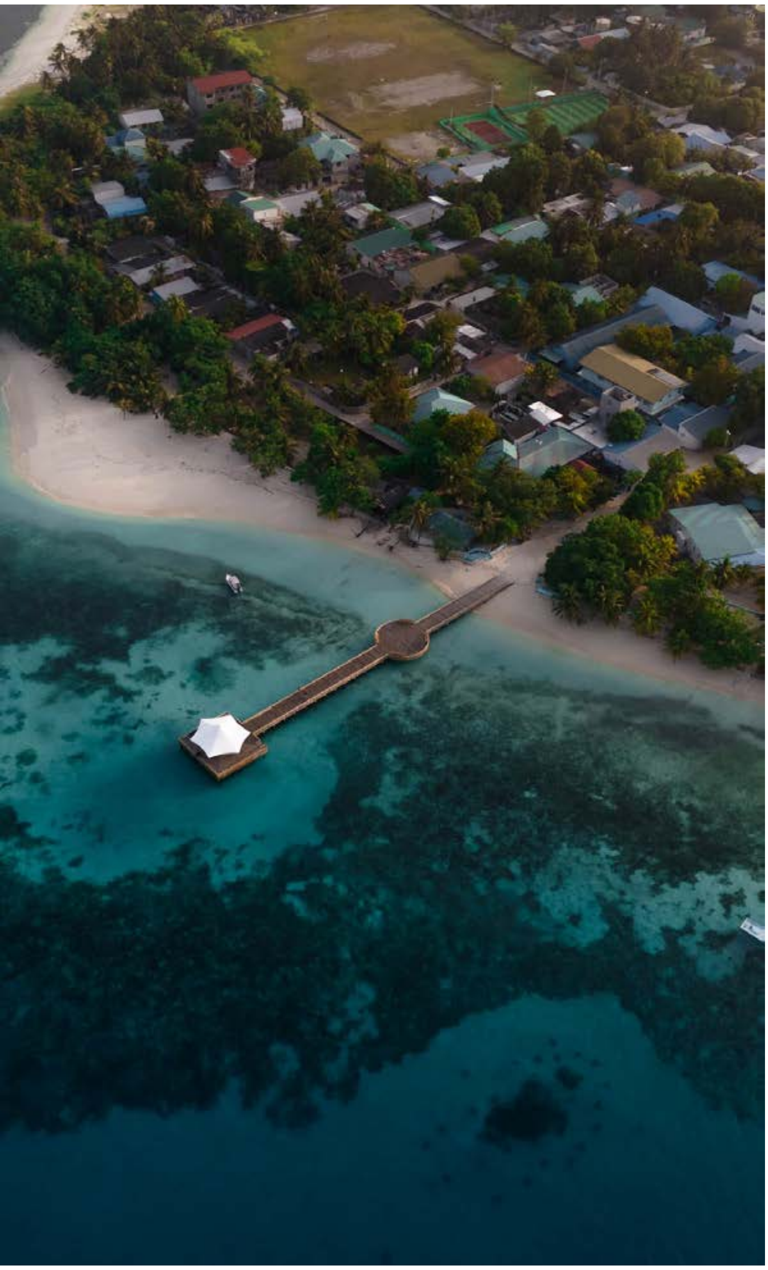
South Ari Atoll

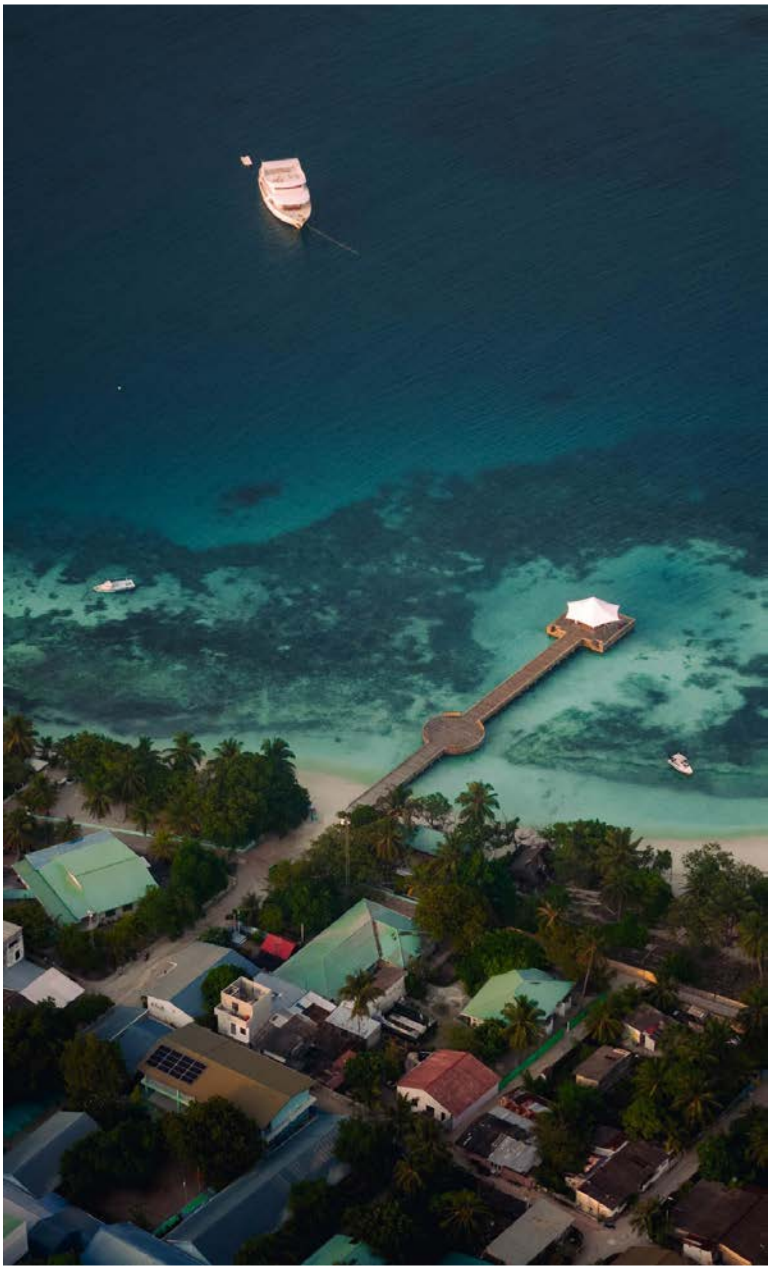


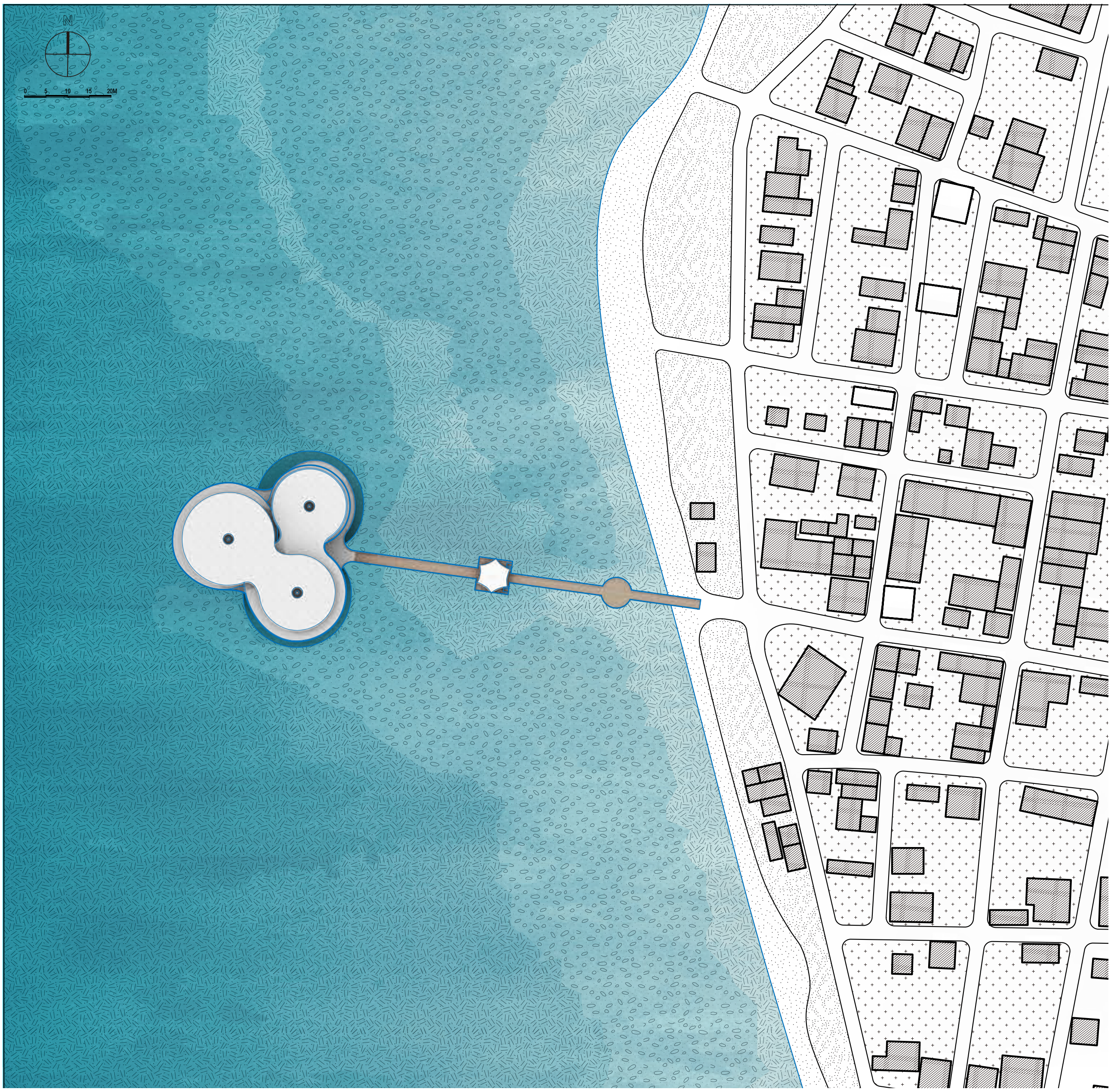
Dhangethi

Atoll Section





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Concept

Foliose Coral - Montipora

Layered

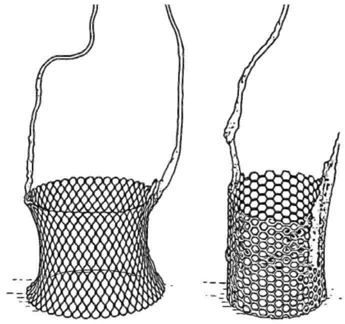
Radial

Modular

+

Findings from Experiment

Curved



Central

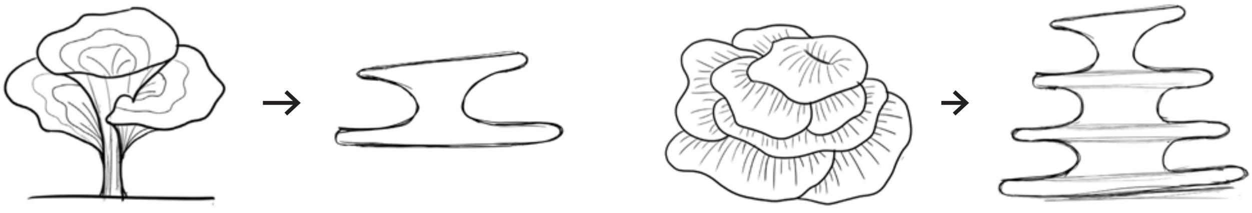
↓

AI Image (Midjourney)

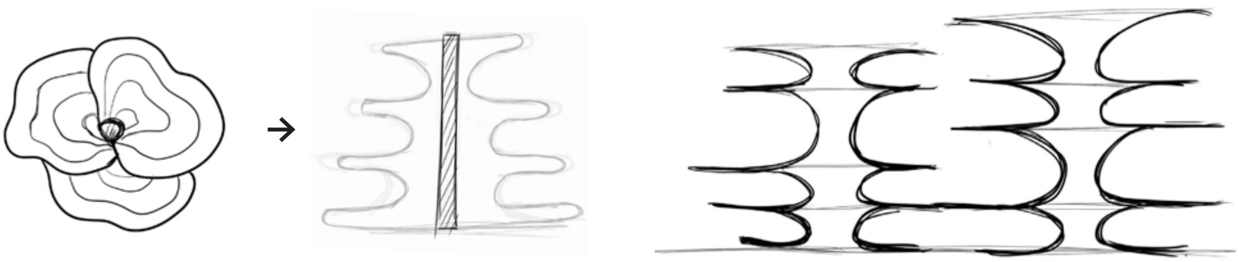
Text prompts: Futuristic underwater hotel inspired by Montipora coral, organic, fluid geometries with smooth. Multiple stacked disc-like platforms spiral dynamically around a central column, evoking coral growth patterns. Open, flowing spaces. Soft bioluminescent lighting, white concrete and steel framework, aquatic plants and coral visible in the background.

Text prompts: Underwater research facility intertwined with living coral, dynamic minimal-surface structures resembling Montipora coral, sustainable marine habitat, floating platforms encrusted with biorock, futuristic oceanic architecture, soft ambient light filtering through water, deep-sea aesthetic, ultra-detailed, cinematic render.

Elements Translation



Modular **Modular System** **Layered** **Terrace**



Radial **Radial Structural System** **Section Prototype**

Based on the morphology of Montipora and the findings from the material experiment, some text prompts were created and typed in Midjourney to generate some AI images (see pictures on the left) for design inspiration. The design concept translates five themes based on all previous explorations:

Modular System

Echoing Montipora's repetitive forms, the section prototype can be stacked by several units. Each unit keeps the same dimensions for the central hollow part, where metal rods can be inserted. However, each shape's height and diameter can be different to create various spatial spaces.

Radial Structural System

Guided by Montipora's radial expansion, each unit takes on a circular, tree-like form with a central void. This informs a core + radial truss structural system, contributing loads efficiently while maintaining an open and column-free interior. Moreover, this radial geometry is also beneficial for growing more even and efficient limestone, as observed during the biorock experiment.

Terrace

Since different units can have different diameters and heights, aiming to create various platforms at the intersection of the modular units. These terraces function as viewing balconies and shading elements.

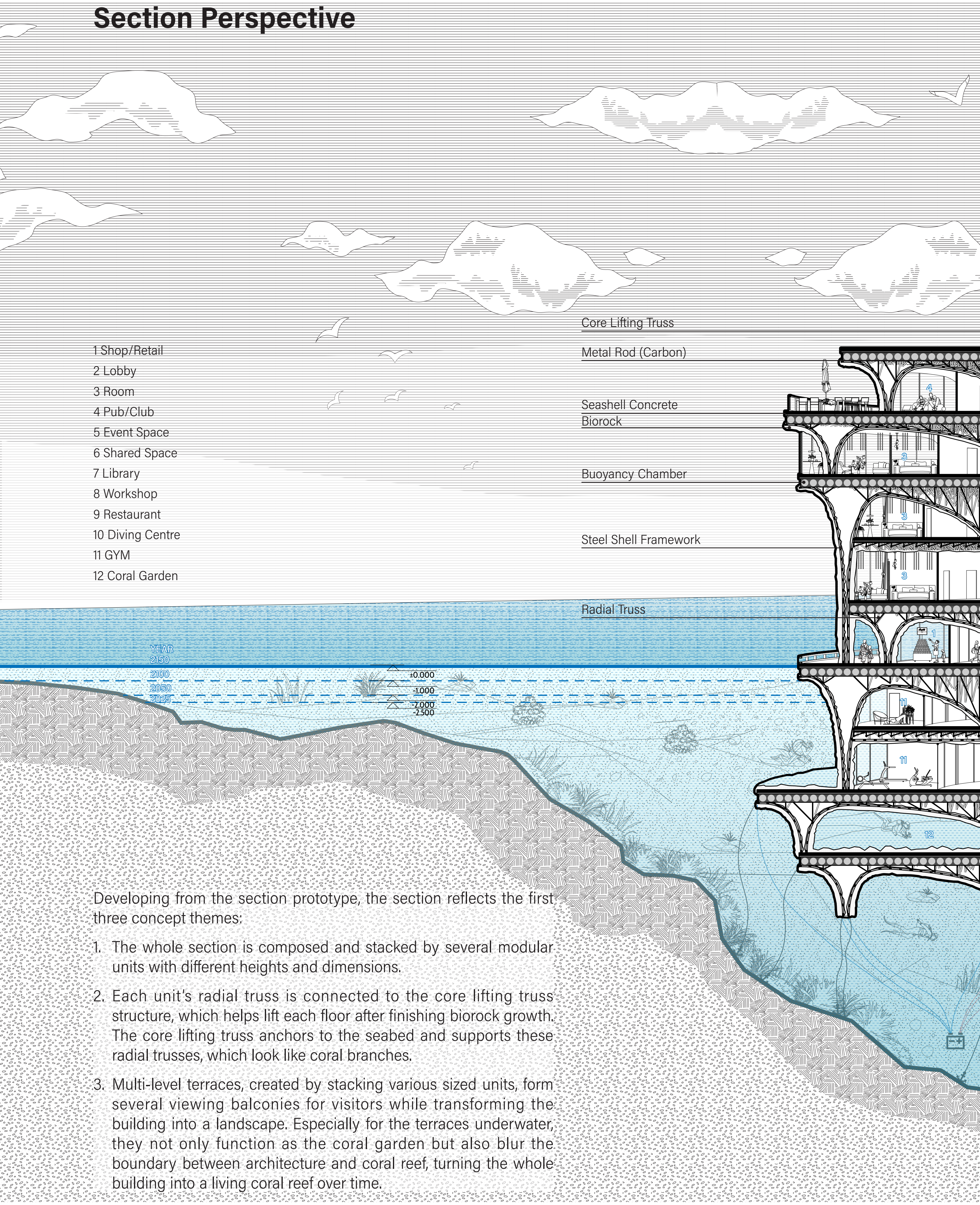
Grow Biorock First, Seashell Concrete Next

In order to create a contrast visual effect, the design adopts the second strategy developed in the material experiment phase: grow biorock with an exposed steel framework first, and then decorate seashell concrete in some parts. For example, use the steel framework to construct the shape of each unit, and then grow the rough and organic biorock texture while casting seashell concrete with the smooth texture as the floor slab and wall system.

Construct Underwater, Live Abovewater

Based on the outcomes of AI-generated visual studies and the better living experience, the project takes a vertical planning strategy: growing the structure underwater, lifting up most of the parts and then floating above water. After the building is lifted up, the abovewater part is mostly used as the hotel function serving for human beings, while the underwater spaces are used as the coral garden and coral research centre for coral cultivation.

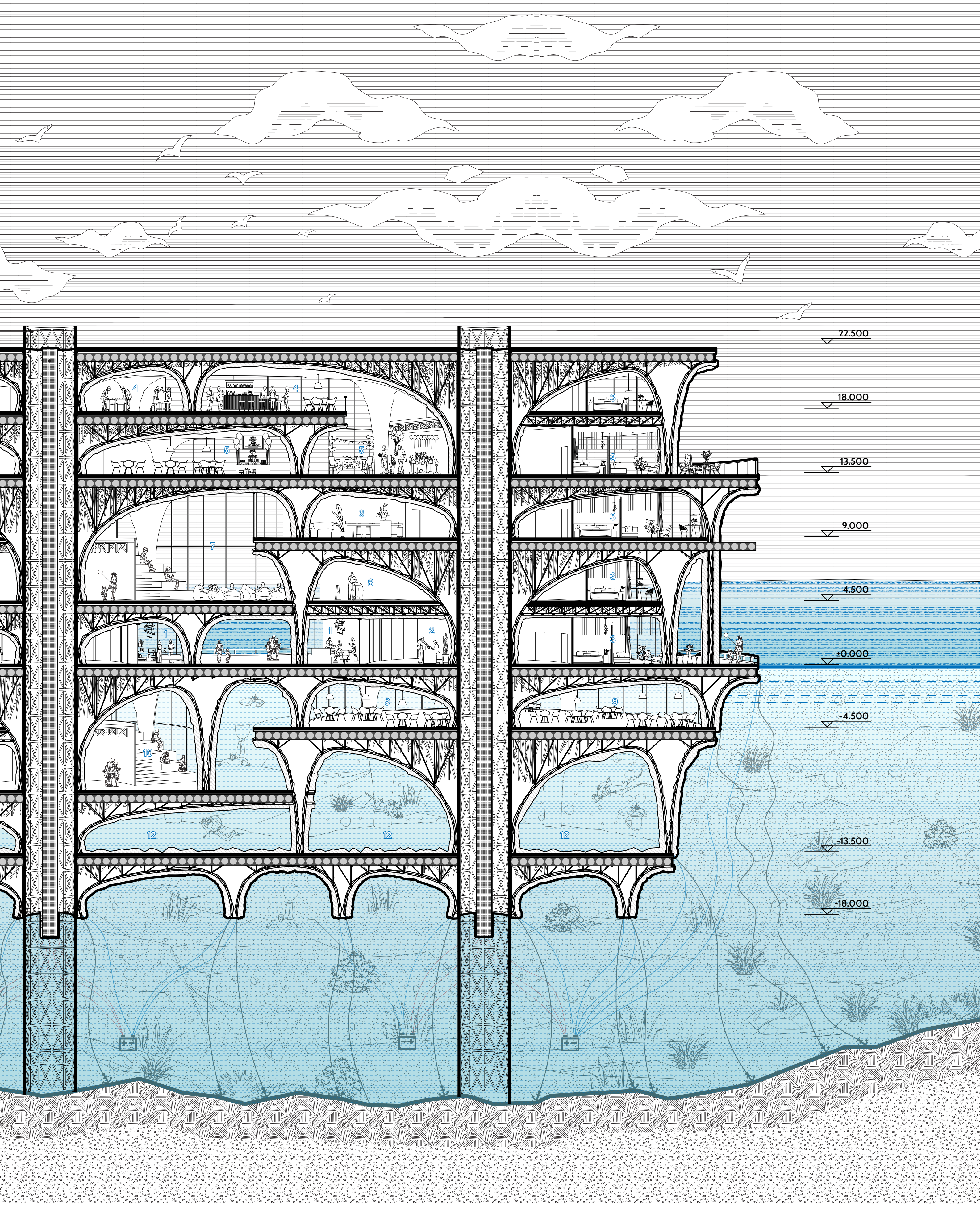
Section Perspective



1 Shop/Retail
2 Lobby
3 Room
4 Pub/Club
5 Event Space
6 Shared Space
7 Library
8 Workshop
9 Restaurant
10 Diving Centre
11 GYM
12 Coral Garden

Developing from the section prototype, the section reflects the first three concept themes:

1. The whole section is composed and stacked by several modular units with different heights and dimensions.
2. Each unit's radial truss is connected to the core lifting truss structure, which helps lift each floor after finishing biorock growth. The core lifting truss anchors to the seabed and supports these radial trusses, which look like coral branches.
3. Multi-level terraces, created by stacking various sized units, form several viewing balconies for visitors while transforming the building into a landscape. Especially for the terraces underwater, they not only function as the coral garden but also blur the boundary between architecture and coral reef, turning the whole building into a living coral reef over time.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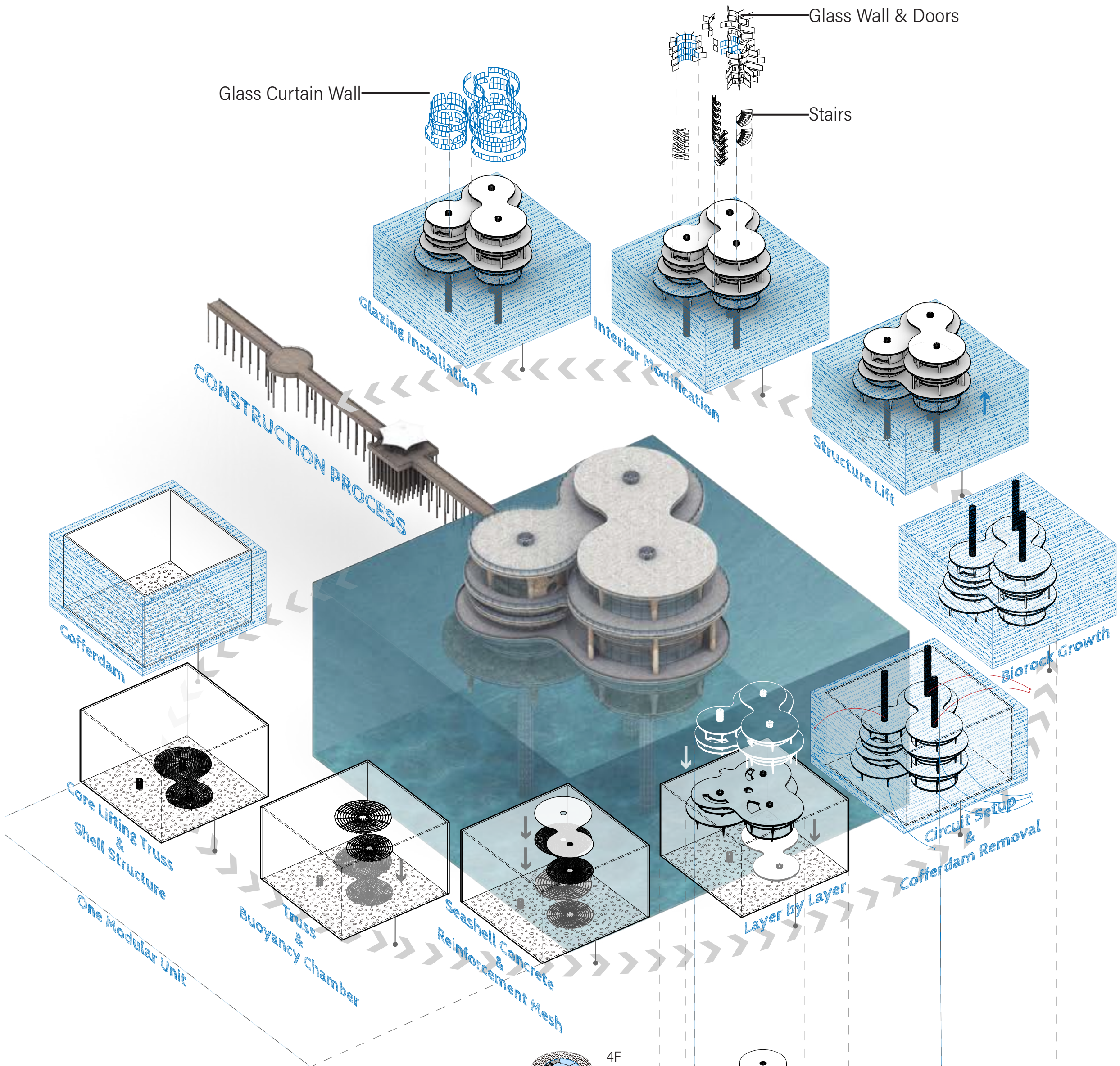
Constuction Process

Underwater Growth, Floating Life

The construction strategy reflects more on the last two concept themes: *Grow Biorock First, Seashell Concrete Next*, and *Construct Underwater, Live Abovewater*.

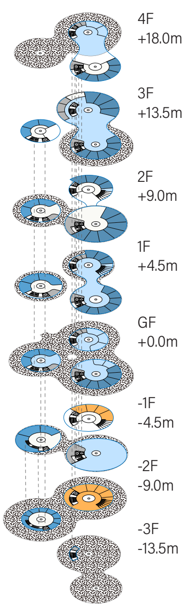
The construction process can be separated into 10 steps (see the diagram on the right).

1. **Cofferdam**
   According to Stannard, L.(2021), there are four types of underwater construction methods: a) caissons, b) cofferdams, c) driven piles, d) off-site building, float and lower. Cofferdams refer to the process of placing an enclosure underwater and then pumping out the water inside to create a dry working environment.
2. **Core Lifting Truss & Shell Structure**
   The building construction starts from the bottom to the top, following the vertical planning strategy. First, the core lifting truss is anchored to the seabed. It serves as the main structure and a lifting mechanism, helping the building rise up from underwater to abovewater. At the same time, the tree-like stell shell structure is constructed around the core. This steel framework is the base for the subsequent biorock growth.
3. **Truss & Buoyancy Chamber**
   The radial truss structures are then built to support the following modular units. Inspired by the MOSE flood barrier project in Venice, buoyancy chambers are inserted within these trusses, which are initially filled with the same water weight as the unit itself. In the building lifting phase, the water inside is replaced by the air, creating a buoyancy force that helps lift the structures from underwater to above the waterline (Designboom, 2020).
4. **Seashell Concrete & Reinforcement Mesh**
   Seashell concrete floor slabs are cast above the truss structure. Before casting, the reinforcement mesh is integrated into the surface of the seashell concrete close to the truss structure. In this case, the partially exposed mesh can start the mineral accretion once in contact with seawater, when the seashell concrete dissolves over time.
5. **Layer by Layer**
   Each unit has the same structural composition, from the bottom to the top: steel shell structure, radial truss, reinforcement mesh, and seashell concrete. Then, these units are stacked upwards layer by layer. At the same time, the load-bearing wall system is integrated, including the vertical circulation area, such as the lift and stairs. This load-bearing wall system is composed of reinforcement mesh and seashell concrete whose strength will then be improved after the biorock technology once the mesh expose to the seawater.
6. **Circuit Setup & Cofferdam Removal**
   The steel shell structure, reinforcement mesh, and truss are connected to the cathode through several wires; the metal rods in the centre are linked to the anode. These wires are then plugged into the power source generated by tidal, wave, or any other renewable energy that provides low-voltage current. Once the electrical circuit is set, the cofferdam is removed, introducing seawater into the structure and initiating the biorock growth process.
7. **Biorock Growth**
   During the mineral accretion process, the steel structure exposed to the marine environment first grows biorock. The growing pattern starts from the hollow centre parts close to the metal rods, highlighting the radial elements that grow from the centre to the outer ring. Simultaneously, the seashell concrete dissolves over time and exposes the rebar inside, which will then be connected to the anode and activate the mineral accretion process. This process also attracts corals to colonize, adding an extra layer on the biorock surface and enhancing its strength.
8. **Structure Lift**
   After obtaining enough thickness and strength of biorock, the structure is lifted up through the core truss and buoyancy chamber. Air is pumped into the buoyancy chamber to replace the water inside, creating buoyancy force, while the core truss provides vertical force to raise each unit gradually above the sea level.
9. **Interior Modification**
   Rough biorock surfaces are selectively polished in areas where the smooth and comfortable material is required, such as rooms and suites. And, the rough biorock texture is preserved in the public spaces to demonstrate this incredible growing material, acting as a large exhibition. Then, the inner walls, stairs, and other interior elements are installed.
10. **Glazing Installation**
    Finally, the glass curtain walls and handrail glazing are installed.

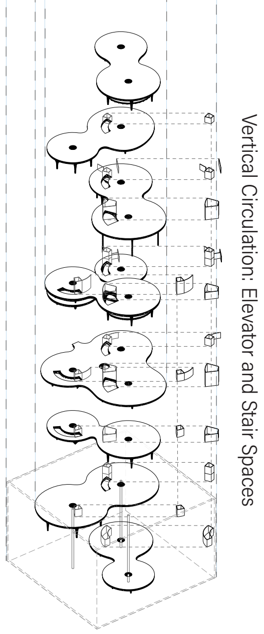


Function		Area (m^2)
Living Area	Rooms	1530
	Lobby	200
Dining Area	Restaurant	550
	Pub/Club	430
Public Spaces	Event Space	400
	Retail/Shop	300
	Library/Workshop	300
Recreation	GYM	250
	Diving Centre	305
Operational Area		520
Corridor		525
Coral Research Centre		1010
TOTAL		6320

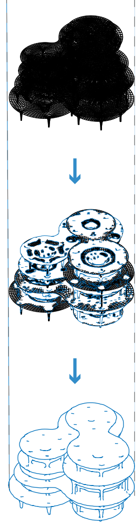
Programme



Functional Layout

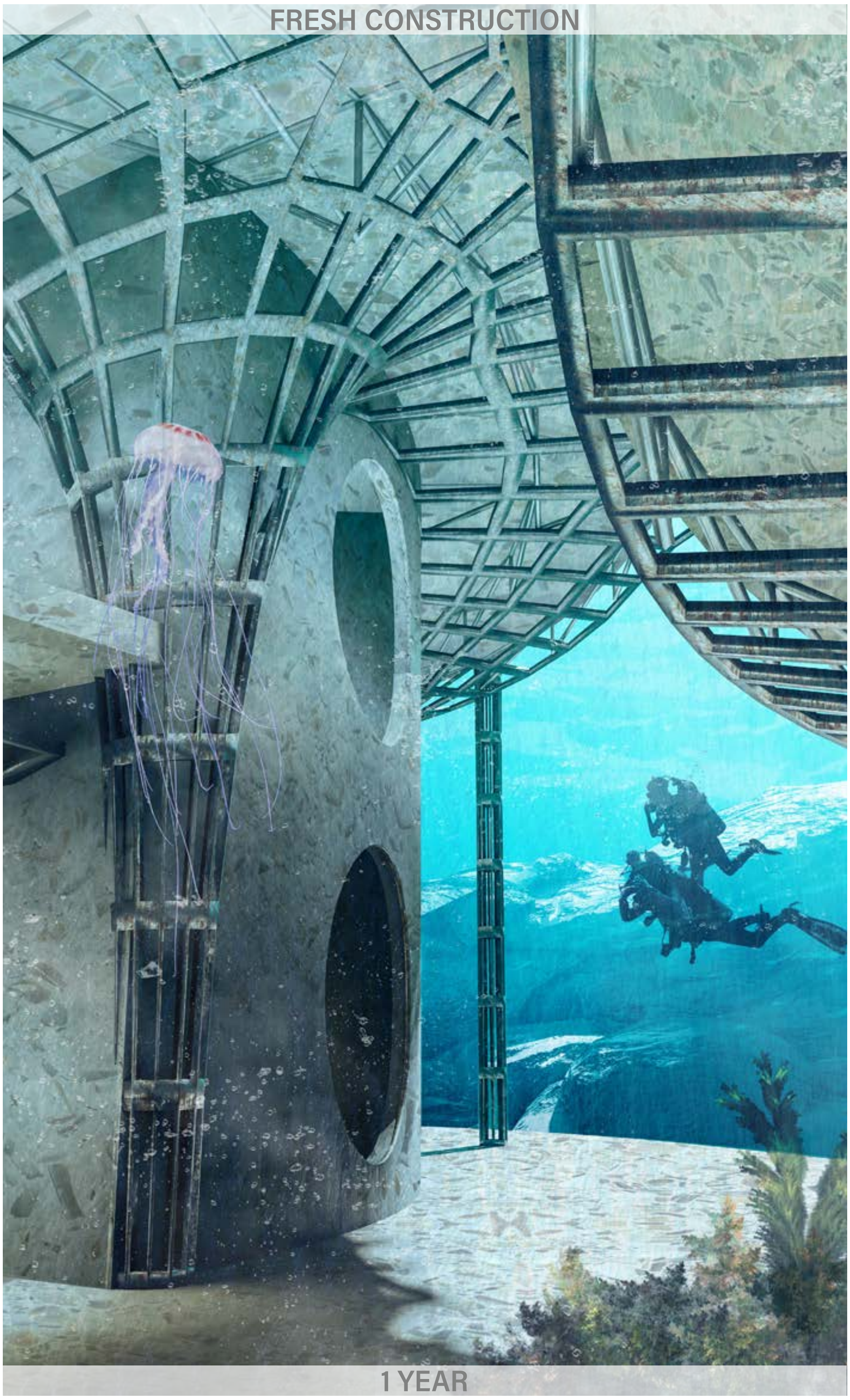


Floor Exploded



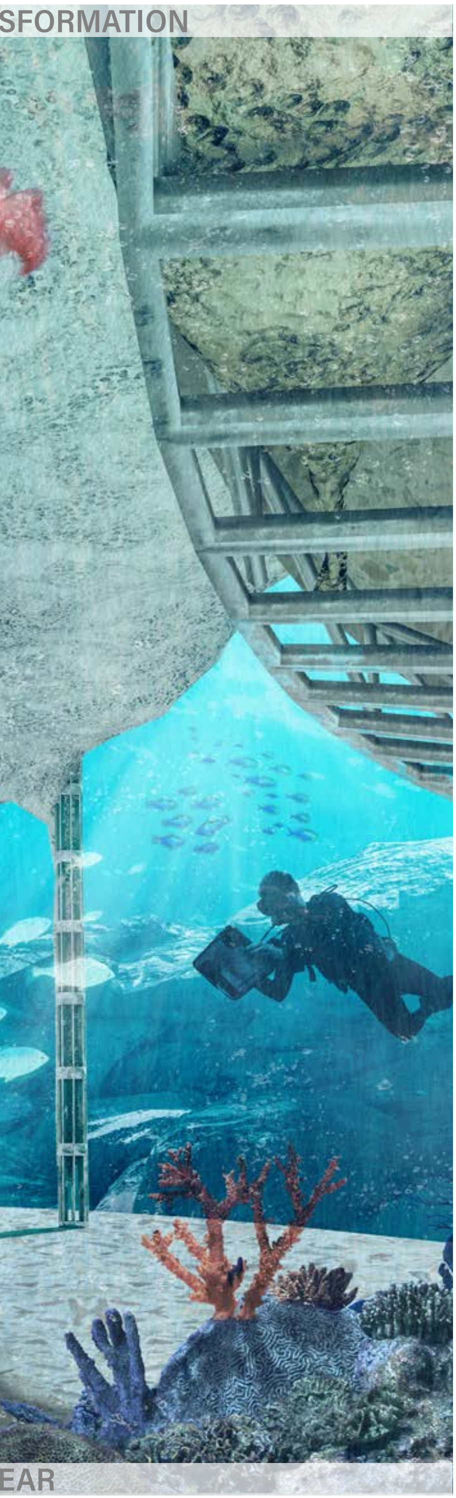
Biorock Growing Process

Material Transformation

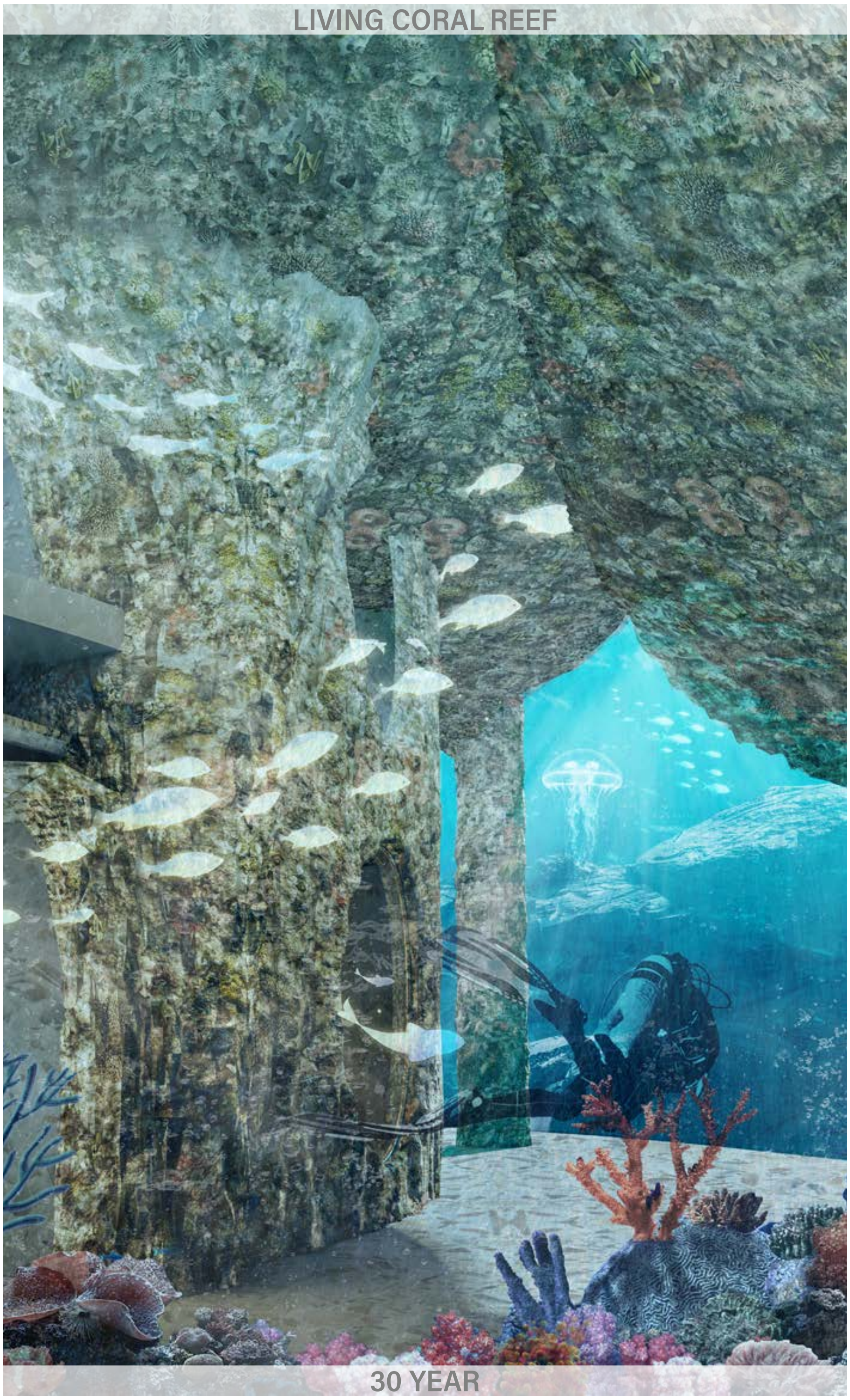


When the building was first constructed, its surface texture was a smooth surface of seashell concrete combined with an exoskeleton steel structure.

Over time, the 'cement'(seashell powder) hydrated material will react with the car produce calcium carbonate (limestone). H seashell concrete will be consumed and d At the same time, biorock technology compensates for the loss of seashell concr

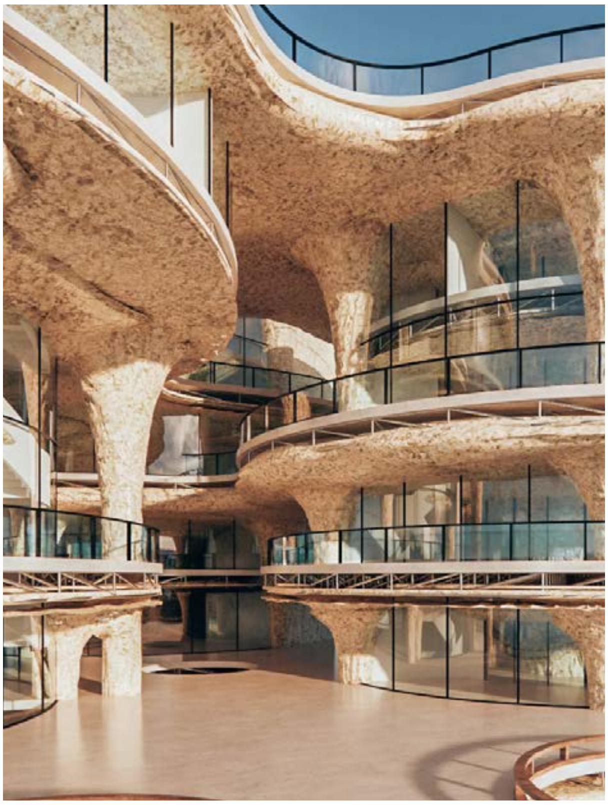


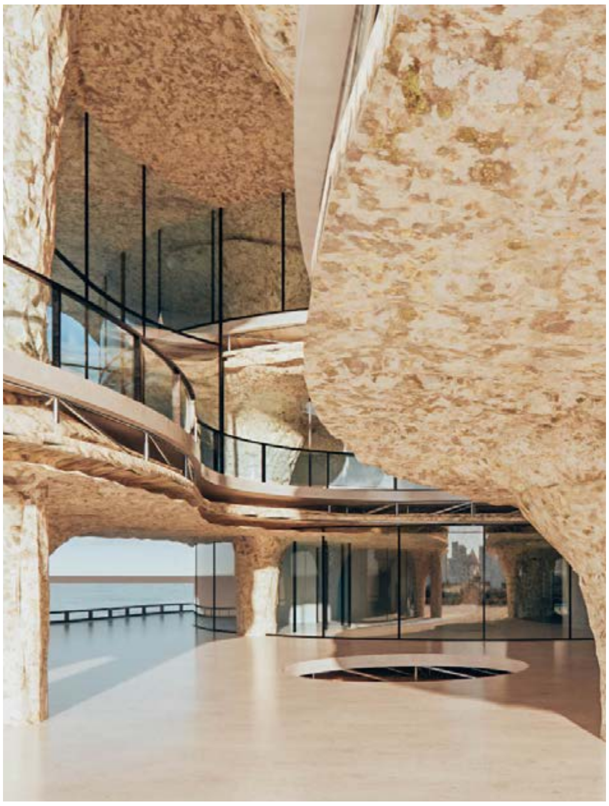
in seashell concrete will hydrate, and this
bon dioxide dissolved in the seawater to
However, this process is very long, so the
issolved before the limestone is produced.
helps grow limestone with time, which
rete and strengthens it.



When a coral dies, its body gradually becomes calcium carbonate (limestone), a process called calcification, which is also known as petrification. This process further increases the limestone on the steel structure and strengthens it, making the building a living coral reef.

Views





CONCLUSION

Conclusion

This thesis explores the potential of combining seashell concrete with biorock technology (mineral accretion) for underwater structures. With the aim of addressing environmental problems such as climate change, sea level rise, and marine ecosystem restoration, this research also provides an alternative way of constructing and living while supporting marine biodiversity. To achieve this, this thesis raises three main questions, which also serve as the support and guideline.

- *How can seashell waste be used as a sustainable alternative to traditional concrete?*
- *How can hybrid materials using seashell concrete and biorock technology be utilized for load-bearing structural purposes?*
- *How can an underwater building be constructed by using this hybrid material combining seashell concrete and biorock technology?*

Through a series of case studies, content analysis, and literature reviews, this project builds a solid foundation of knowledge for the material experiment and design proposal phase. The first two research questions were developed and answered by four material experiments: traditional concrete, seashell concrete, biorock technology, and hybrid material. These labs examined the properties, behaviours, limitations and potential applications of seashell concrete, biorock and their combination.

The outcomes from the concrete experiments demonstrate that seashell waste has the ability to replace the aggregates and cement in traditional concrete, but it lacks strength for load-bearing structures. This research tested and refined material recipes to enhance strength by adding admixtures like clay, gypsum and steel slag ash, showing that the additives can improve seashell concrete's performance. Thus, seashell concrete can be a sustainable alternative when it is ultilized for non-load bearing purposes such as wall panels and decorative elements.

The hybrid material test introduced a method of combining seashell concrete with biorock - inserting a wire mesh into the concrete mould surface, casting seashell concrete, and finally setting up a circuit after curing. The results from this lab prove that seashell concrete can improve the efficiency of biorock growth, while the biorock forms a solid, rough, and organic coating layer that strengthens and protects the structure. Although the hybrid test was limited in time and scale, the interplay between the two materials demonstrates the potential of this approach to meet the load-bearing requirement for underwater structures.

Observations about the growth pattern in the biorock technology experiment further guided the form finding for the design proposal phase and the construction logic for combining this hybrid material. Two construction strategies were proposed:

1. Cast seashell concrete first, embedding steel wire mesh on the surface or inside as reinforcement. As the seashell concrete dissolves over time, once the steel material is exposed to seawater, the biorock grows. In this approach, biorock is more like an add-on component reinforcing the concrete's strength while generating a protective coating.
2. Grow biorock first using the steel framework through mineral accretion in seawater, followed by the decoration with seashell concrete.

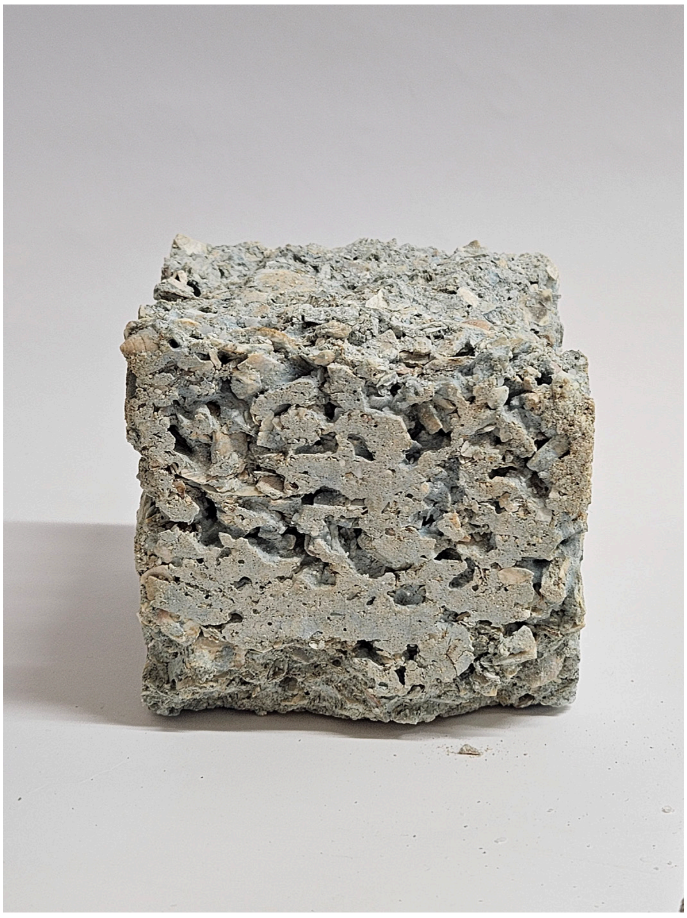
Both strategies have benefits and limitations. The first one can provide a smooth seashell concrete surface, but it may have lower strength in the early stages, meaning it might not support a large-scale underwater project. In contrast, the second approach allows the biorock to grow first, generating a rough and organic texture and creating a strong structural skeleton. However, this method is time-consuming because it may take many years to grow enough thickness and strength with the growing rate of 1-2 cm per year.

The final design proposal uses these findings to address the last research question. Inspired by the site analysis, Montipora coral, and AI image, five concept themes were developed and used as the design guideline, which are: a) Modular System; b) Radial Structural System; c) Terrace; d) Grow Biorock First, Seashell Concrete Next; e) Construct Unerwater, and Live Abovewater.

Located at Dhangethi Jetty in the Maldives, the underwater hotel with a coral research centre translates three elements - modular, radial and layered- from Montipora coral morphology into a modular, radial and terraced architectural system. Each modular unit varies in height and diameter to create platforms, viewing balconies and shading spaces which imitate Montipora coral's spatial logic. Following the second construction strategy, the structure is first built underwater with steel shell frameworks to grow biorock, followed by the selective application of seashell concrete for floor slabs and walls. The contrast between rough biorock and smooth seashell concrete creates an attractive visual effect and material expression. After growing enough biorock, the building is then lifted abovewater using buoyancy chambers integrated into the radial trusses with the help of the core lifting truss system. The underwater parts are the coral research labs and coral cultivation garden, while the abovewater sections are hotel and recreation spaces. This combination enables the building itself not only to be a lone structure, but also a living coral reef.

By combining this hybrid material innovation with coral reef restoration, this thesis offers a blueprint for future coastal cities. It proposes a sustainable and regenerative construction strategy that grows, adapts, and evolves in harmony with the marine environment. This strategy transforms the building itself into a part of the marine life, proving that human habitats can grow with it, work with it and even become part of it.

Although the project is speculative and many experiments are imperfect due to time and material limitations, it still provides a potential concept for buildings that grow underwater using biorock and seashell concrete. In the fast-paced building industry, this approach with a long building cycle may not be up to date and practical. However, these strategies could offer sustainable and resilient solutions and become possible for real-world application one day with further research and development.



STUDENT BACKGROUND

EDUCATION

08/2023 - 06/2025 Gothenburg, Sweden

CHALMERS UNIVERSITY OF TECHNOLOGY

Master of Architecture and Urban Design

- Master's Thesis: Hybrid Solutions for Underwater Structures with Seashell Concrete and Biorock Technology
- Project: Robotic Fabrication of Biomaterial Facade and Spaces
- Project: Integrating AI in Architectural Design to Preserve Cultural Identity

09/2016 - 06/2021 Guangzhou, China

GUANGDONG UNIVERSITY OF TECHNOLOGY

Bachelor of Architecture

- Bachelor's Thesis: Design for the Activation, Utilisation and Renewal of Qiao Wei in Duhu Town, Taishan City

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CRACOW UNIVERSITY OF TECHNOLOGY

Exchange Program

- Project: Contemporary Interventions in European Historical Cities

WORKING EXPERIENCES

07/2021 - 02/2022 Shenzhen, China

ZHUBO DESIGN

Assistant Architect in Construction Department II

- Worked on residential projects, factory renovation, as well as canopy design;
- Took part in scheme biddings, analysis and rendering drawings, text layout and production;
- Responsible for construction drawings, using SketchUp and Rhino to create models.

10/2020 - 01/2021 Shenzhen, China

AREP

Intern - Design Assistant

- Worked on urban railway interior design, and TOD projects;
- Participated in scheme biddings, 3D models productions, drawing analysis and text layouts;
- Responsible for changing and adjusting CAD and the area measurement.

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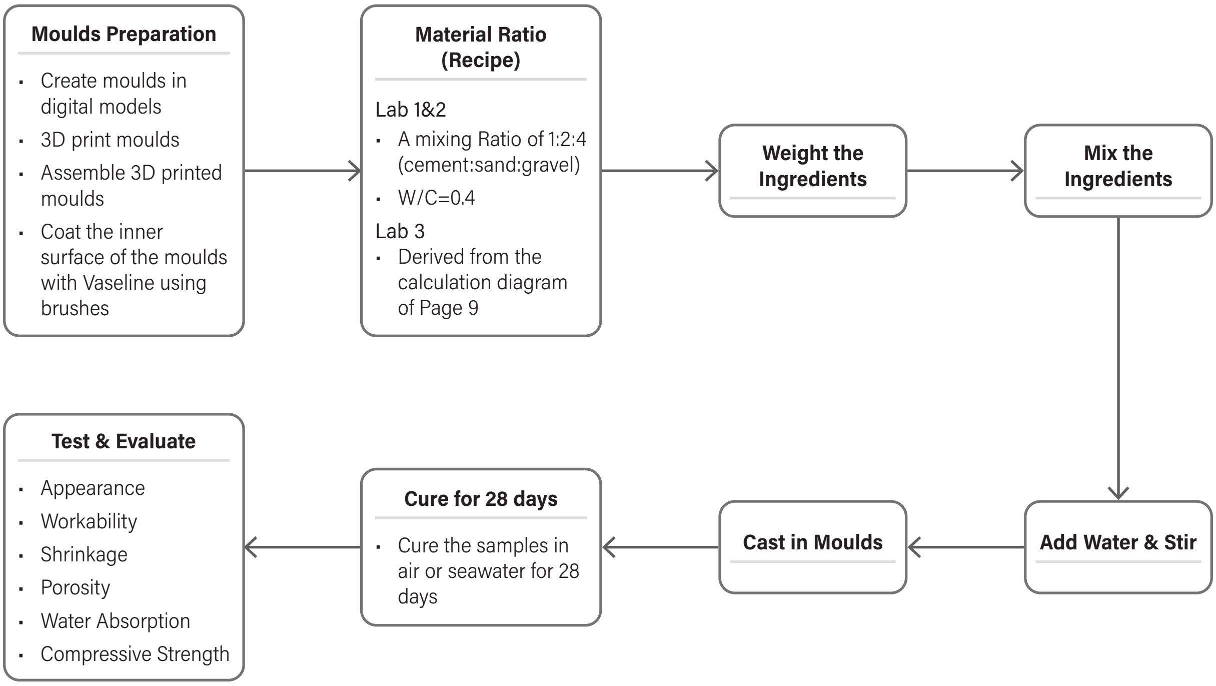
APPENDIX

Material Lab Diary
AI Use

Experiment 1 - Traditional Concrete

Steps



Ingredients Recipe

Lab	Mix Ratio	Sample	Shape	Dimension	Sand(g)	Gravel(g)	Cement (g)	W/C	Curing Area
Lab 1	1:2:4	TC1	Cube	10cm×10cm×10cm	685.71	1371.43	342.86	0.4	Air
		TC2	Tile	10cm×10cm×2cm	137.14	274.29	68.57		
Lab 2	1:2:4	TC3	Cube	5cm×5cm×5cm	85.71	171.43	42.86	0.4	Air
Lab 3	1:1.7:1.9	TC4	Cube	5cm×5cm×5cm	104.68	122.58	63.56	0.45	Air
		TC6							Seawater

This experiment served as a control group to compare the properties of traditional concrete with those of the experimental materials(seashell concrete), including compressive strength, durability, water absorption and so on.

NOTE: TC - Traditional Concrete; W/C - Water/Cement
The calculations for material batching are described in detail on Page 10-11.

Tools


Brushes
Coating (petroleum jelly, wax or oil)
Moulds
Container for Mixing
Measuring Cup
Masking Tape
Kitchen Scale
Stirring Tool
Trowel
Sieves
Measuring Spoons
Sandpaper
Gloves

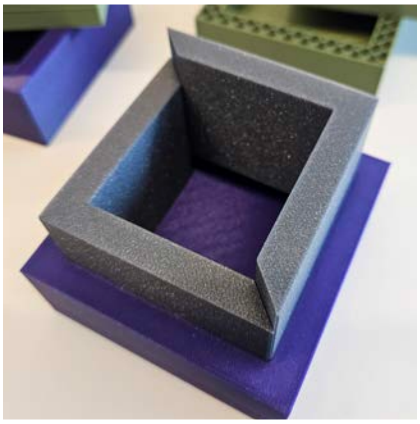
Lab Diary

LAB	Lab 1	Lab 2	Lab 3
Working Time	2024.10.27 - 2024.10.29	2024.12.01 - 2024.12.04	2025.03.01 - 2025.03.05
Curing Time	2024.10.29 - 2024.11.26	2024.12.04 - 2025.01.01	2025.03.05 - 2025.04.04
Extra Operations in the Steps	▪ Added water configured with blue acrylic paint to the concrete mix instead of pure water. ▪ After the samples solidified in the air for 48 hours, they were removed from the moulds and then cured in the air for 28 days. ▪ Submerged the cured samples in pure water for 48 hours to test their water absorption.	▪ Enhanced vibration after casting concrete paste in the mould. ▪ After the samples solidified in the air for 48 hours, they were removed from the moulds and then cured in the air for 28 days. ▪ Submerged the cured sample in pure water for 48 hours to test its water absorption.	▪ Poured the paste into the mould layer by layer and vibrated sufficiently. ▪ Tapped the mould with a trowel to enhance the vibration. ▪ Placed a weight over the moulds and compacted them. ▪ After the samples solidified in the air for 80 hours, they were removed from the moulds and placed in the air for 48 hours. ▪ Sample TC4 was cured in air for 28 days while TC5 was cured in seawater for 28 days.
Findings	**Material Redundancy:** The amount of material calculated based on the formula was almost half more than what was needed. **Poor Binding:** The mix did not hold well initially; more water had to be added. **Slow Setting Time:** Concrete took longer to set in PLA 3D-printed moulds, which was more than 24 hours. **Surface Voids:** Samples showed porous surfaces and cracks after demolding, which might be caused by insufficient vibration, inadequate compaction and a high water-cement ratio.	**Fewer Voids and Cracks:** After the optimization, there were fewer voids and cracks than in lab 1. **Air Holes:** Tiny holes still appeared on both the top and bottom surfaces. **Deformation:** The base of the sample showed poor verticality due to leakage during casting.	**Recipe Accuracy:** TC4 used exact calculated values but did not fill the 5x5x5 cm cube, meaning tolerances must be considered. **Defects in TC5:** Despite using the same recipe as TC4 (multiplied by 110% overall), TC5 showed more cracks and voids, probably due to insufficient vibration and compaction. **White Substances on TC5:** White deposits appeared on the sample's surface after curing in seawater.
Improvement for next Labs	**Recipe Optimization:** Used 50–70% of the original amount to reduce waste and avoid redundancy. **Water-Cement Ratio:** Determined the proportions, added water gradually while stirring, and reduced the addition of extra water. **Vibration & Compaction:** Vibrated and compacted thoroughly after pouring the paste to remove air and minimize cracks.	**Recipe Redefinition:** A new recipe was developed for Lab 3 based on three reference sources (see Note). The detailed calculation diagram is on Page 9. **Mould Sealing:** Ensured tight sealing of the mould base and sides to prevent leakage. **Enhance Vibration and Compaction:** Extended the vibration time and compact the paste heavily.	**Layered Vibration:** Manual vibration may not remove deeper air bubbles. Try casting the mix in layers and vibrating each layer. Alternatively, use a simple mechanical vibrator to improve vibration. **Staged Compaction:** Manual compaction with light pressure may not entirely eliminate internal voids. Consider repeating the compaction process in stages or using heavier weights for better results.

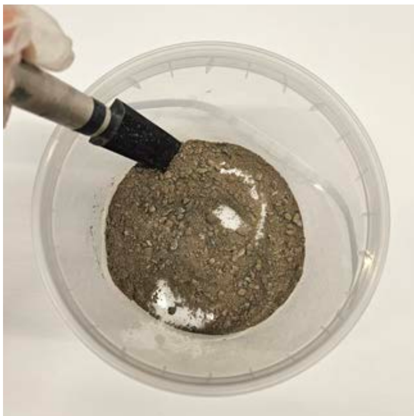
NOTE: As the final design site is located in the Maldives, the calculations, formulas and values in the diagrams are based on references from three main sources: *Concrete: Microstructure, Properties, and Materials, 4th Edition, IS 10262:2019 (Indian Standard for Concrete Mix Proportioning), and ACI CODE-318-19(22): Building Code Requirements for Structural Concrete and Commentary.*

Lab 1

Lab 2

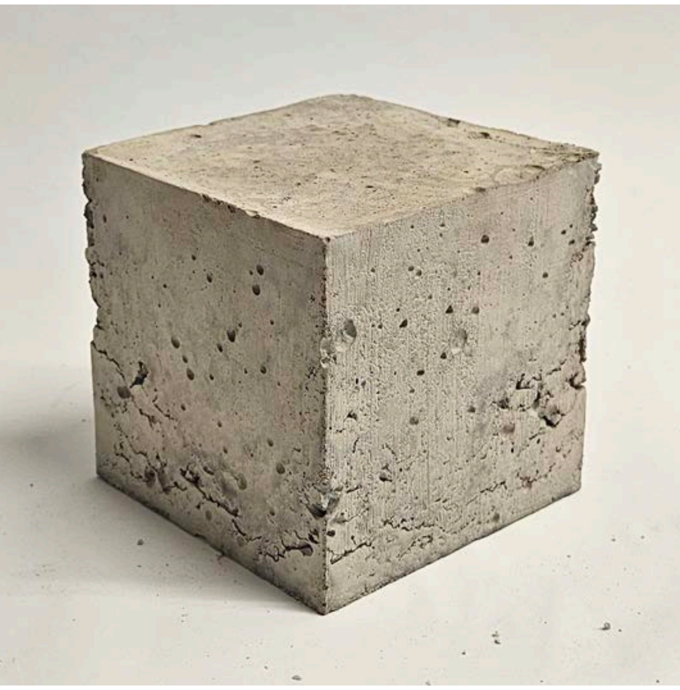


Lab 3



Sample

TC1



Appearance

Workability

Density

Porosity

Water Absorption

TC2

Appearance

Workability

Density

Porosity

Water Absorption

TC4

Appearance

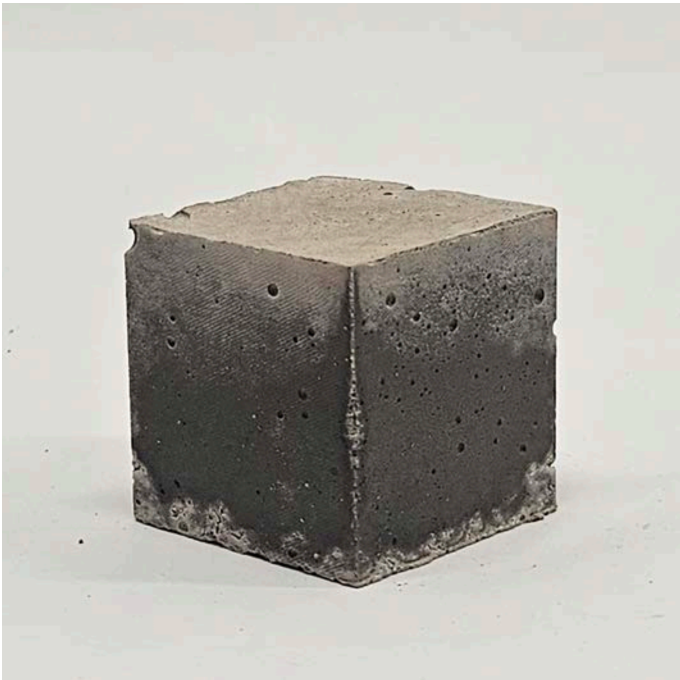
Workability

Density

Porosity

Water Absorption

TC5 (Before Curing in Seawater)



Appearance

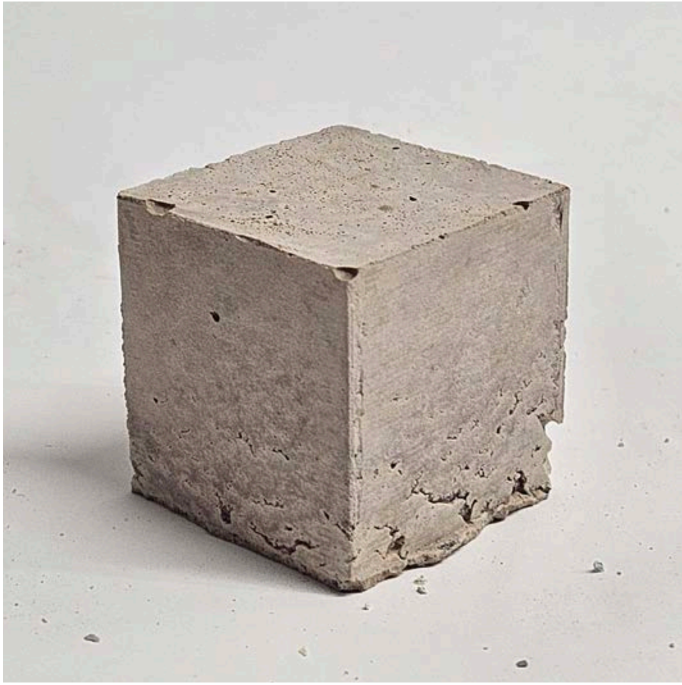
Workability

Density

Porosity

Water Absorption

TC3



Appearance

Workability

Density

Porosity

Water Absorption

TC5 (After Curing in Seawater)

NOTE: Detailed data comparisons are provided on Page 49.

Concrete Mix Proportioning Calculation Diagram

1. **Define Objectives**
   a. Required Compressive Strength: **M35 (35 Mpa at 28 days)**
   b. Cement: Portland Composite Cement (Byggcement from Heidelberg Materials)
   c. Maximum Size of Aggregate: **10MM**
   d. Exposure Conditions: Severe (Marine Environment) (Zone III)
   e. Workability (Slump): **150 - 200mm** [recommended for underwater structures from Neville (2011)].

2. **Material Properties**
   a. Specific Gravity of Cement: **3.0**
   b. Specific Gravity of Coarse Aggregate: **2.7**
   c. Specific Gravity of Fine Aggregate (Sandlådesand RÖLUNDA): **2.6**

3. **Target Strength**

   $f'_{ck} = f_{ck} + 1.65\ S$ or $f'_{ck} = f_{ck} + X$

   whichever is higher

   f'_{ck} = target average compressive strength at 28 days

   f_{ck} = characteristic compressive strength at 28 days

   S = standard deviation

   X = factor based on grade of concrete.

   From *Table 2 of IS-10262, S = 5 N/mm²*

   From *Table 1 of IS-10262, X = 6.5*

   Therefore,

   $f'_{ck} = f_{ck} + 1.65\ S = 35 + 1.65 \times 5 = 43.25\ N/mm^2$

   $f'_{ck} = f_{ck} + X = 35 + 6.5 = 41.5\ N/mm^2$

4. **Estimated Air Content**

   From *Table 3 of IS-10262*, the amount of air entrainment in normal (non-air-entrained) conctete is estimated to be **1.5%** for a nominal maximum aggregate size of 10 mm.

5. **Water-Cement Ratio (W/C)**

   0.45

6. **Estimation of the Water Content**

   From *Table 4 of IS-10262,*

   Water Content = 208 kg/m^3

NOTE: Adapted from IS 10262:2019 (Bureau of Indian Standards, 2019), pp. 16-18.

7. Calculation of the Cement

W/C = 0.45

Cement Content = 208 / 0.45 ≈ 462.22 kg/m^3

8. Proportion of Volume of Aggregates

From *Table 5 of IS-10262*, the ratio of 10 mm size coarse aggregate to fine aggregate (zone III) is 0.52 at 0.50 water/cement ratio. For every 0.05 decrease in the water-cement ratio, the ratio of coarse aggregate volume to total aggregate volume increases by 0.01. Therefore,

The proportion of volume of coarse aggregate = 0.52 + 0.01 = 0.53

The proportion of volume of fine aggregate = 1 - 0.53 = 0.47

9. Mix Calculations

a. Assume the total volume of concrete is 1 m^3

b. Volume of entrapped air = 1.5% × 1 m^3 = 0.015 m^3

c. Volume of cement = (Mass of cement/Specific gravity of cement) × 1/1000
= (462.22/3.0) × 1/1000 ≈ 0.154 m^3

d. Volume of water= (Mass of water/Specific gravity of water) × 1/1000
= (208/1) × 1/1000 = 0.208 m^3

e. Volume of all aggregates = [(a-b)-(c+d)]
= [(1-0.015) - (0.154+0.208) = 0.623 m^3

f. Mass of coarse aggregates= Volume of all aggregates × Proportion of coarse aggregate × Specific gravity of coarse aggregate × 1000
= 0.623 × 0.53 × 2.7 × 1000 = 891.51 kg

g. Mass of fine aggregates= Volume of all aggregates × Proportion of fine aggregate × Specific gravity of fine aggregate × 1000
= 0.623 × 0.47 × 2.6 × 1000 = 761.31 kg

10. Final Recipe

Cement = 462.22 kg/m^3

Water = 208 kg/m^3

Fine aggregate = 761.31 kg/m^3

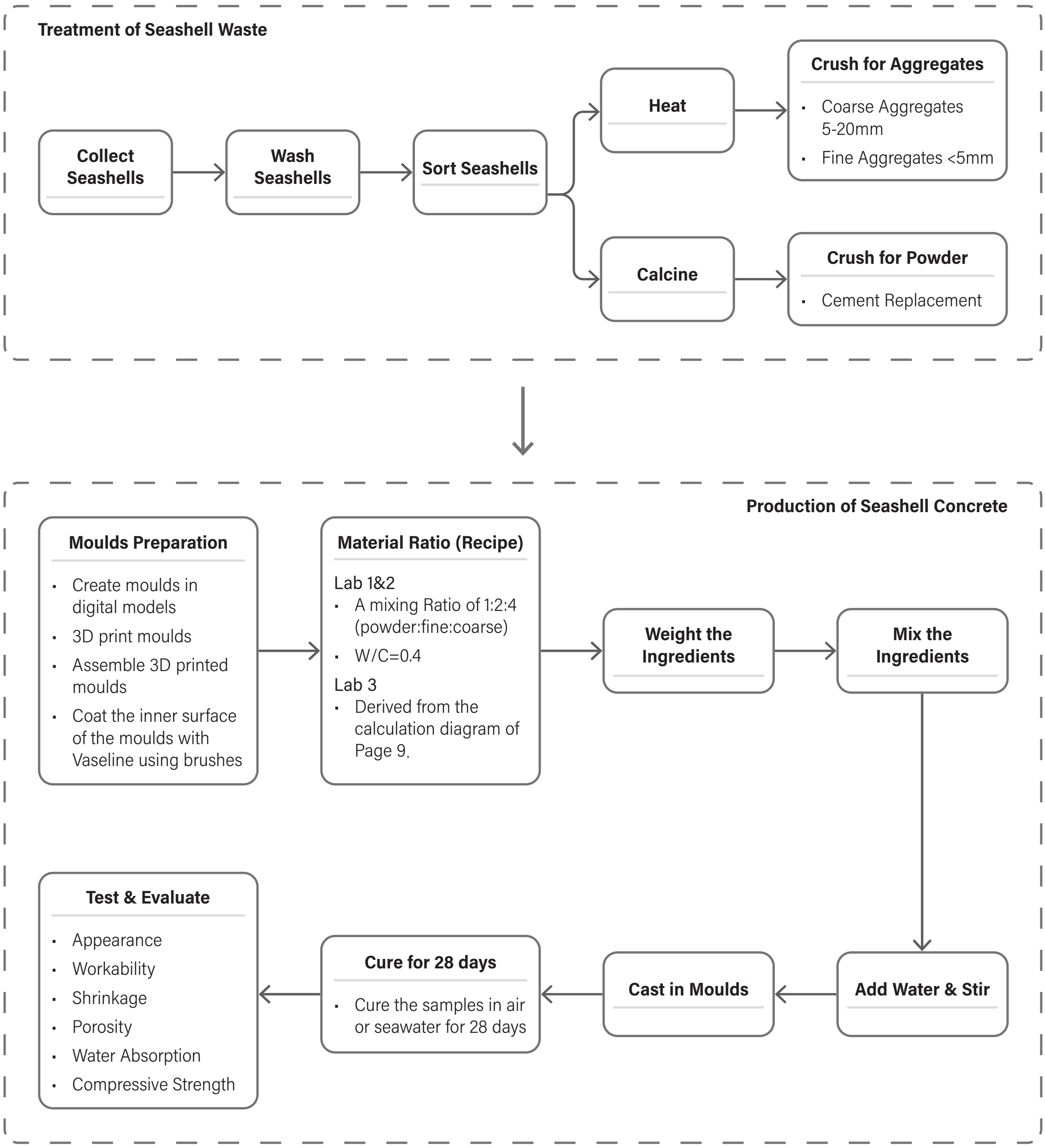
Coarse aggregate = 891.51 kg/m^3

Water-Cement ratio = 0.45

NOTE: Adapted from IS 10262:2019 (Bureau of Indian Standards, 2019), pp. 16-18.

Experiment 2 - Seashell Concrete

Steps



Seashell concrete was the experimental group, and the whole process can be roughly divided into 3 phases: seashell treatment, seashell concrete manufacturing and testing phase.

Tools

Brushes

Coating (petroleum jelly, wax or oil)

Masking Tape

Moulds

Container for Mixing

Measuring Cup

Mortar and Pestle.

Tongs

Kitchen Scale

Stirring Tool

Trowel

Sieves

Measuring Spoons

Sandpaper

Gloves

Orthers: Saucepan, Oven, Calcination Equipment

Ingredients Recipe

<table>
<tr><th>Lab</th><th>Sample</th><th>Dimension
(cm×cm×cm)</th><th>Fine Aggragates
(g)</th><th>Coarse Aggragates
(g)</th><th>Seashell Powder
(g)</th><th>Clay
(g)</th><th>Steel Slag Ash
(g)</th><th>Gypsum
(g)</th><th>W/SP</th><th>Curing Area</th></tr>
<tr><td rowspan="2">Lab 1</td><td>SC1</td><td>10×10×10</td><td>685.71</td><td>1371.43</td><td>342.86</td><td>0</td><td>0</td><td>0</td><td>0.4</td><td rowspan="2">Air</td></tr>
<tr><td>SC2</td><td>10×10×2</td><td>137.14</td><td>274.29</td><td>68.57</td><td>0</td><td>0</td><td>0</td><td>0.4</td></tr>
<tr><td colspan="11"></td></tr>
<tr><td rowspan="6">Lab 2</td><td>SC3</td><td rowspan="6">5×5×5</td><td>42.86</td><td>85.72</td><td>21.43
(100%)</td><td>0</td><td>0</td><td>0</td><td>0.85</td><td rowspan="6">Air</td></tr>
<tr><td>SC4</td><td>42.86</td><td>85.72</td><td>17.14
(80%)</td><td>4.29
(20%)</td><td>0</td><td rowspan="5">1.07
(5%)</td><td rowspan="5">0.61</td></tr>
<tr><td>SC5</td><td>42.86</td><td>85.72</td><td>12.86
(60%)</td><td>7.50
(35%)</td><td>1.07
(5%)</td></tr>
<tr><td>SC6</td><td>42.86</td><td>85.72</td><td>12.86
(60%)</td><td>6.43
(30%)</td><td>2.15
(10%)</td></tr>
<tr><td>SC7</td><td>42.86</td><td>85.72</td><td>12.86
(60%)</td><td>4.29
(20%)</td><td>4.29
(20%)</td></tr>
<tr><td>SC8</td><td>42.86</td><td>85.72</td><td>17.14
(80%)</td><td>3.22
(15%)</td><td>1.07
(5%)</td></tr>
<tr><td colspan="11"></td></tr>
<tr><td rowspan="8">Lab 3</td><td>SC9</td><td rowspan="8">5×5×5</td><td>104.68</td><td>122.58</td><td>63.56
(100%)</td><td>0</td><td>0</td><td>0</td><td>0.91</td><td rowspan="8">Seawater</td></tr>
<tr><td>SC10</td><td>104.68</td><td>122.58</td><td>47.67
(75%)</td><td>12.72
(20%)</td><td>0</td><td rowspan="7">3.18
(5%)</td><td>0.78</td></tr>
<tr><td>SC11</td><td>104.68</td><td>122.58</td><td>41.32
(65%)</td><td>19.06
(30%)</td><td>0</td><td rowspan="6">0.86</td></tr>
<tr><td>SC12</td><td>104.68</td><td>122.58</td><td>41.32
(65%)</td><td>15.90
(25%)</td><td>3.18
(5%)</td></tr>
<tr><td>SC13</td><td>104.68</td><td>122.58</td><td>41.32
(65%)</td><td>12.72
(20%)</td><td>6.36
(10%)</td></tr>
<tr><td>SC14</td><td>104.68</td><td>122.58</td><td>41.32
(65%)</td><td>6.36
(10%)</td><td>12.72
(20%)</td></tr>
<tr><td>SC15</td><td>104.68</td><td>122.58</td><td>41.32
(65%)</td><td>3.18
(5%)</td><td>15.90
(25%)</td></tr>
<tr><td>SC16</td><td>104.68</td><td>122.58</td><td>47.67
(75%)</td><td>9.54
(15%)</td><td>3.18
(5%)</td></tr>
</table>

According to Wikipedia, cement consists of lime (CaO), silica (SiO2), and alumina (Al2O3), which is also a fine powder formed by heating limestone (CaCO3) and clay minerals at high temperatures in a kiln to form clinker, to which about 5% gypsum is added and ground. Therefore, admixtures such as clay, slag ash, and gypsum are mixed with seashell powder in different proportions to test the optimal seashell 'cement'.

NOTE: SC - Seashell Concrete; W/SP - Water/Seashell Powder
The calculations for material ratio are described in detail on Page 9.

Treatment of Seashell Waste

1. **Collect seashells**

   Collected seashells from Brännö Galterö Naturreservat.

2. **Wash seashells**

   Washed seashells with a brush.

   Soaked in water for a few hours.

   Washed again under running water

   Boiled seashells for 15 minutes.

3. **Sort seashells**

   Classified the seashells according to the type and shape of seashells.

   Picked out some aesthetic seashells for decoration purposes

4. **Heat and calcine seashells**

   Heated the seashells in the oven at 200℃ for 40 minutes to remove impurities, bacteria and moisture and also made them easier to grind.

   Oyster shells were selected and calcined at a high temperature of 800℃ for 4h (Seo, Park, Yang, & Jang, 2019), and measured the weight of the oyster shells before and after calcination.

5. **Crush seashells**

   Grind calcined seashells into powder for use as cement replacement.

   Crush and sieve heated seashells into fine and coarse aggregates as replacement of sand and gravel.








Lab Diary

LAB	Lab 1	
Working Time	2024.10.27 - 2024.10.29	202
Curing Time	2024.10.29 - 2024.11.26	202
Extra Operations in the Steps	▪ Added water configured with blue acrylic paint to the concrete mix instead of pure water. The amount of water used does not strictly follow the calculated amount but is added to the paste according to its condition. ▪ After the samples solidified in the air for 48 hours, they were removed from the moulds and then cured in the air for 28 days. ▪ Submerged the cured samples in pure water for 48 hours to test their water absorption.	▪ Dried and ground the clay int ▪ Poured the paste into the mou ▪ After the samples solidified cured in the air for 28 days. ▪ Submerged the cured sample absorption.
Findings	**Material Redundancy:** The amount of material calculated based on the formula was almost half more than what was needed. **Poor Workability:** The irregular, flaky shape of seashell particles made mixing and stirring more difficult than traditional concrete. **More Water:** More water was required than calculated because of the water-absorbing properties of seashell particles, the larger gaps between particles, or bonding needs (Zhu et al., 2024). **Extended Setting Time:** Apart from the PLA 3D-printed moulds, which enlarged the setting time, seashell concrete needed more time to set than traditional concrete. **Severe Surface Voids:** The voids were more apparent than conventional concrete, which could be caused by insufficient vibration and compaction or oversized shell particles, resulting in poor bonding. **Fragility:** SC1 was fragile because some particles easily fell off and partially collapsed when accidentally placed under the traditional concrete sample.	**Voids and Cracks:** Despite th appeared on all the samples. others remained rough and rock **Inconsistent surface appear** additives had different surface others were rough and rocky. Th - Irregular Shape and High P water and raise the possibility 2018). - Low Binder Content caused p **Fragility:** All samples were demoulding, which might be resulting in weak binding. **Low Strength:** One sample pressure during curing. **Water Absorption:** Samples to internal voids and cracks. concrete. Those samples with a SC3 (100% seashell-based). (Se
Improvement for next Labs	**Recipe Optimization:** Used 50–70% of the original amount to reduce waste and avoid redundancy. **Smaller Aggregates:** Adjusted the size of seashell aggregates into smaller sizes for better bonding and reducing the gaps between particles. **Enhance Vibration and Compaction:** Vibrated and compacted thoroughly after pouring the paste to remove air and minimize cracks. **Add Admixture:** Added some admixtures like clay and slag ash to enhance the strength of seashell concrete.	**Recipe Redefinition:** Like wha recipe was developed for Lab 3 9. **Enhance Vibration and Compa** the paste heavily. **Extend Setting Time:** Prolong to make sure the seashell concr **Optimize Admixture Proportio** proportion in concrete makin enhance the strength, reduce p

Lab 2	Lab 3
4.12.01 - 2024.12.04	2025.03.01 - 2025.03.05
4.12.04 - 2025.01.01	2025.03.05 - 2025.04.04

o powder.
uld layer by layer and vibrated sufficiently.
in the air for 48 hours, they were and then

s in pure water for 48 hours to test their water

- Poured the paste into the mould layer by layer and vibrated sufficiently.
- Tapped the mould with a trowel to enhance the vibration.
- Placed a weight over the moulds and compacted them.
- After the samples solidified in the air for 80 hours, they were removed from the moulds and placed in the air for 48 hours.
- All samples were then cured in artificial seawater (3.5% salinity) for 28 days.

e improvement from previous lads, voids still Some samples had smoother finishes, while ky.

ance: Samples with different proportions of e appearances. Some were smoother, while he main reasons for these are,
orosity of seashell aggregates require more of air pockets between aggregates (Mo et al.,

poor adhesion and porous textures.

fragile and broke near the corners during caused by insufficient initial curing time,

was accidentally crushed by gentle hand

released air bubbles when submerged due They absorbed more water than traditional admixtures had lower absorption compared to e Page 49 for data comparison.)

Improved Appearance: All samples' appearances, such as flatness and verticality, improved. The new recipe with the seashell 'cement' ratio bound the aggregates better than in previous labs, reducing the situation in which particles fell off.

Colour and Texture: SC9 (100% seashell-based) has the lightest colour and most beautiful outlooking, while samples with more clay or steel slag ash were darker. Those samples with more steel slag ash had fewer cracks, smoother surfaces, and better verticality, but they had more circular air bubbles on the surfaces.

White Substances: Each sample releases many bubbles when placed in the artificial Seawater with a salinity of 3.5%. After a while, the Seawater becomes turbid because of some chemical reactions, such as,
- Calcium Leaching: Calcium hydroxide ($Ca(OH)_2$) in cement dissolves and reacts with CO_2 in seawater, forming white deposits which might be aragonite ($CaCO_3$) (Mehta & Monteiro, 2014).
- Salinization: Salt crystallization (NaCl, MgSO4, etc.) occurs after seawater evaporation (Kosmatka et al., 2002).

Cured in Seawater (28 Days): The samples became fragile, and the parts touched with the tongs crumbled easily when the sample was removed with them. More air bubbles appeared on samples' surfaces showing partial dissolution. The white substances the author assumed were the main composition of limestone ($CaCO_3$) were more like powder particles.

Water Absorption: Samples containing steel slag ash or clay were better compacted and less porous than those with 100% seashells (See Page 49 for data comparison). Samples cured in seawater had lower water absorption, which shows that seawater can help enhance hydration or improve compactness.

t had been done in traditional concrete, a new 3. The detailed calculation diagram is on Page

action: Extend the vibration time and compact

ed the setting time from 48 hours to 80 hours rete samples were solidified.

on: Read more references about the admixture g to find a better admixture ratio that can orosity and improve water resistance.

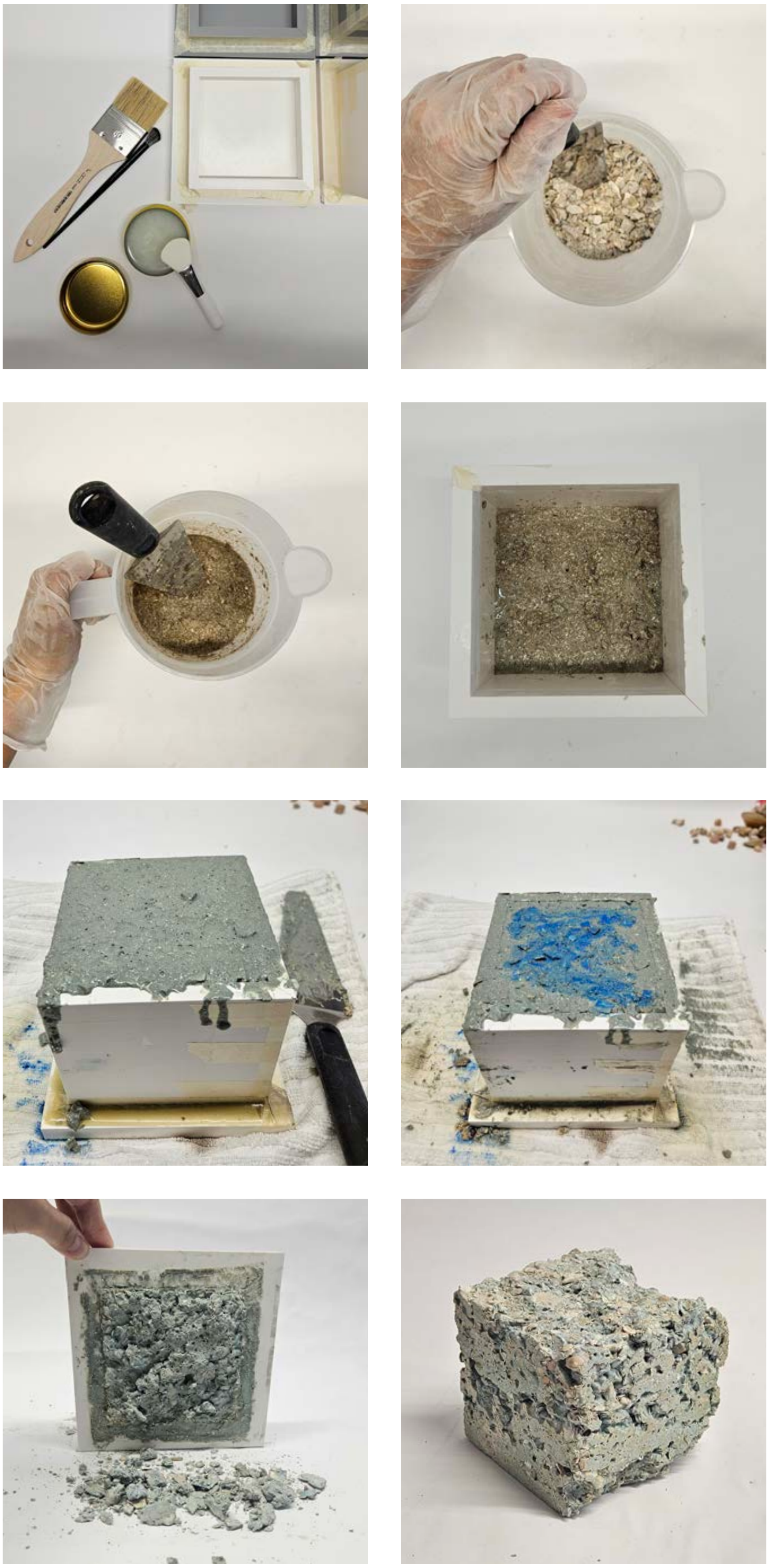
Sample Selection: Picked four samples with optimized properties close to those of traditional concrete and used their recipe for the Hybrid Material Experiment.

Layered Vibration: Manual vibration may not remove deeper air bubbles. Try casting the mix in layers and vibrating each layer. Alternatively, use a simple mechanical vibrator to improve vibration.

Staged Compaction: Manual compaction with light pressure may not entirely eliminate internal voids. Consider repeating the compaction process in stages or using heavier weights for better results.

Lab Process Image

Lab 1



Lab

b 2

Lab 3

Sample

SC1

Appearance | Workability | Density

Porosity | Water Absorption

SC2

Appearance | Workability | Density

Porosity | Water Absorption

SC3

Appearance | Workability | Density

Porosity | Water Absorption

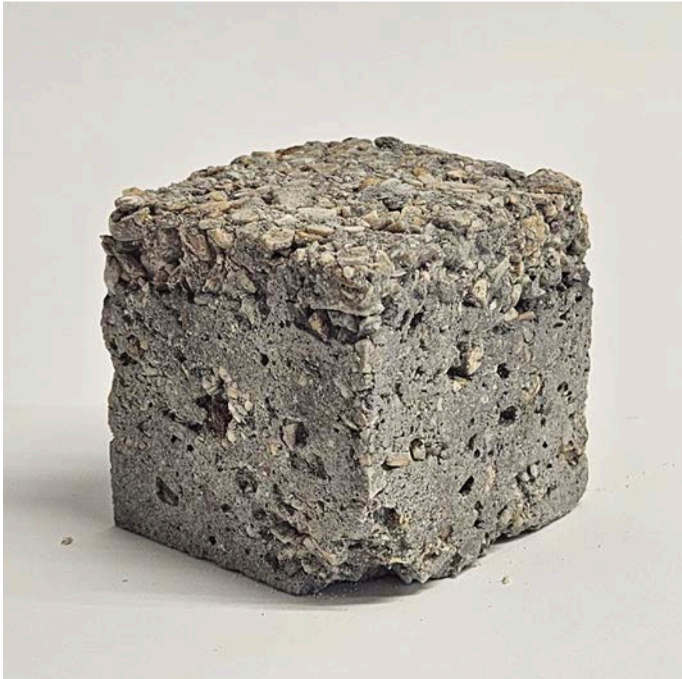
SC4

Appearance | Workability | Density

Porosity | Water Absorption

NOTE: Detailed data comparisons are provided on Page 49.

SC5



Appearance

Workability

Density

Porosity

Water Absorption

SC6

Appearance

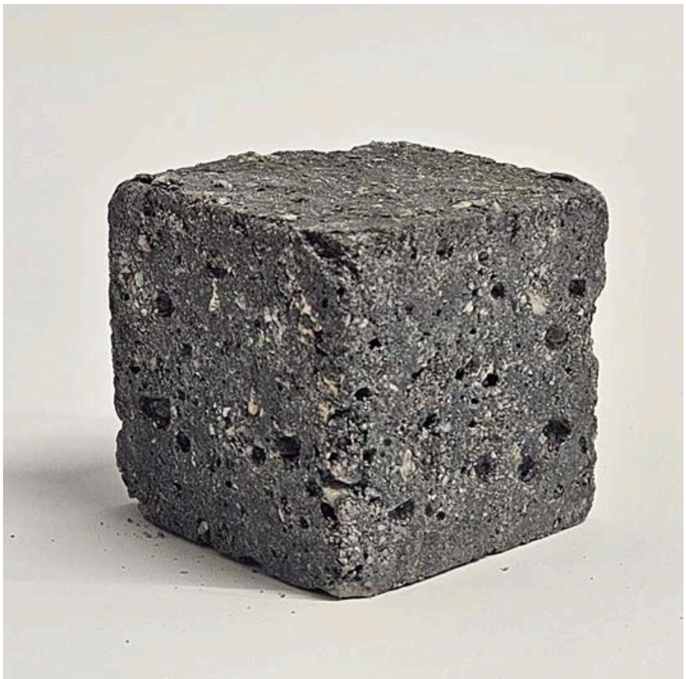
Workability

Density

Porosity

Water Absorption

SC7



Appearance

Workability

Density

Porosity

Water Absorption

SC8

Appearance

Workability

Density

Porosity

Water Absorption

NOTE: Detailed data comparisons are provided on Page 49.

Sample

SC9

Appearance
Workability
Density
Porosity
Water Absorption

SC10

Appearance
Workability
Density
Porosity
Water Absorption

SC11

Appearance
Workability
Density
Porosity
Water Absorption

SC12

Appearance
Workability
Density
Porosity
Water Absorption

NOTE: Detailed data comparisons are provided on Page 49.

SC13

Appearance

Workability

Density

Porosity

Water Absorption

SC14

Appearance

Workability

Density

Porosity

Water Absorption

SC15

Appearance

Workability

Density

Porosity

Water Absorption

SC16

Appearance

Workability

Density

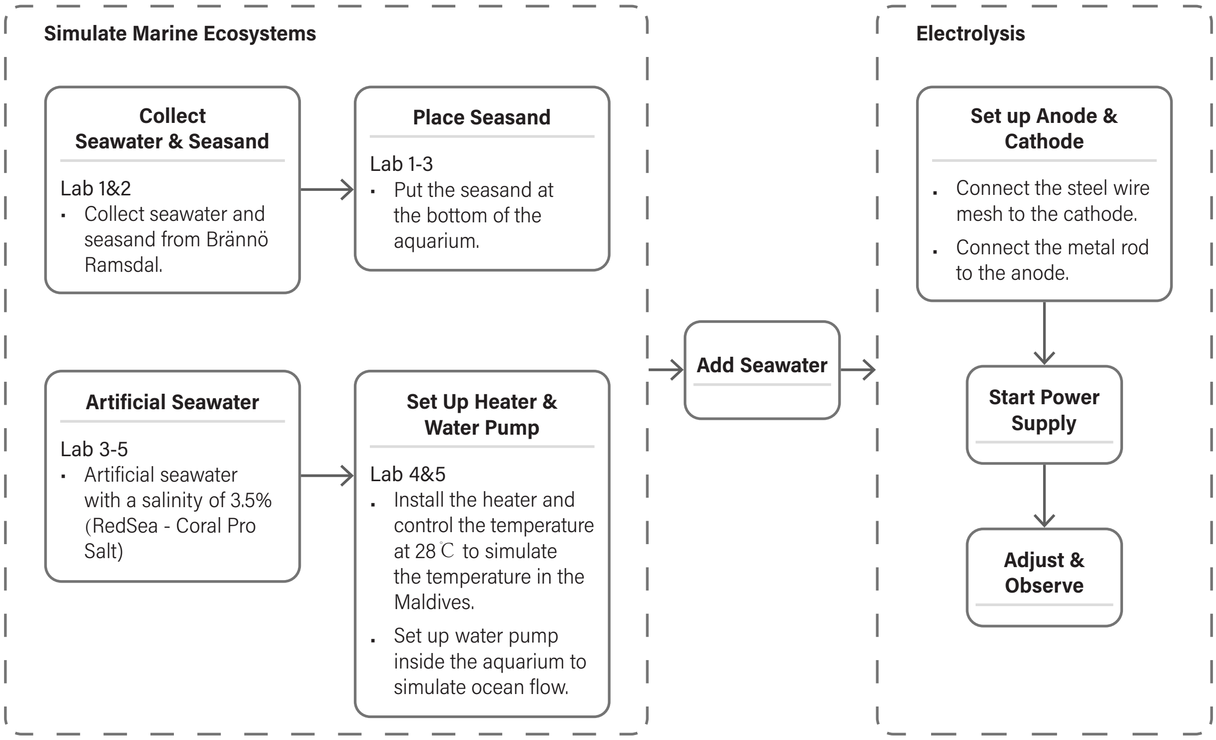
Porosity

Water Absorption

NOTE: Detailed data comparisons are provided on Page 49.

Experiment 3 - Biorock Technology

Steps

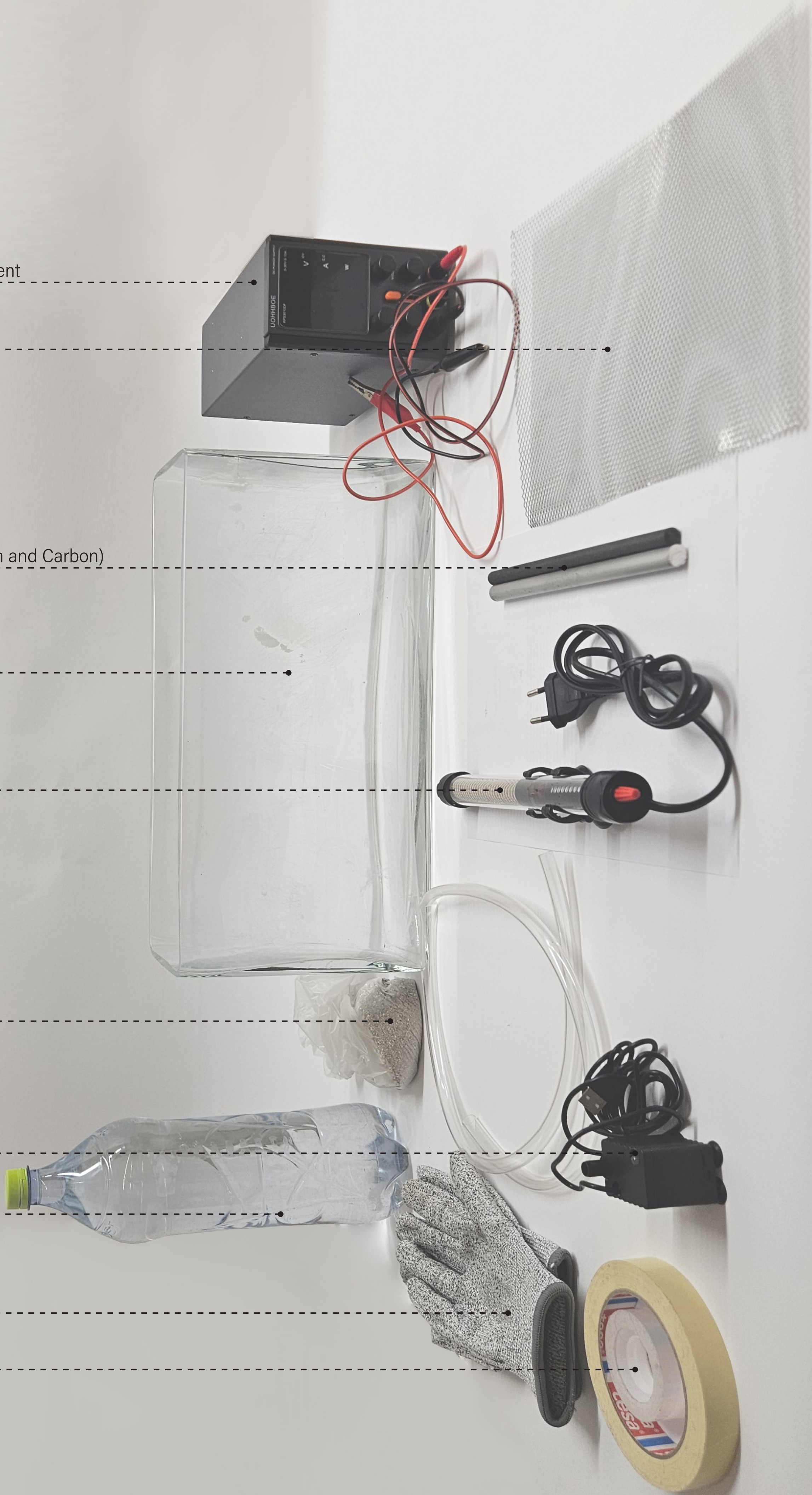


Recipe

Lab	Sample	Steel Wire Mesh	Metal Rod		Seawater (L)	Direct Current		Time Use
		Dimension (cm×cm)	Type	Dimension (cm×mm)		Voltage (V)	Current (A)	Hour (h)
Lab 1	B1	12×12 (straight)	Aluminium	20×12	5.3	6	0.50 - 2.00	72
Lab 2	B2	12×8.5 (straight)	Aluminium	20×12	6.2	6	0.45 - 2.70	168
	B3	20×12 (curved)						
Lab 3	B4	20×12 (curved)	Carbon	20×10	6.2	3	0.092 - 0.119	168
Lab 4	B5	Complex Shape	Carbon	30×12	15.8	3.5	0.231 - 1.4	672
Lab 5	B6	Cylinder (h:5cm Φ:4.5)	Carbon	30×12	6	3	0.53-0.92	168
	B7	Waisted Cylinder (h:5cm Φ:4.5)						

The seawater was initially set up at 5 litres, and additional seawater needed to be added to ensure enough ions to react during the electrolysis process. During the electrolysis process, the voltage was fixed while the currents changed every second, so the chart recorded the current value interval.

Tools



DC Powder Supplyment

Steel Wire Mesh

Metal Rod (Aluminum and Carbon)

Aquarium

Thermostatic Heater

Seasand

Small Water Pump

Seawater

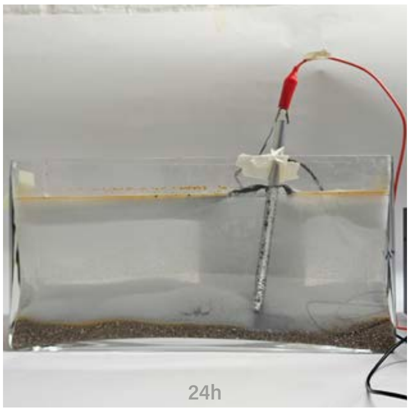
Gloves

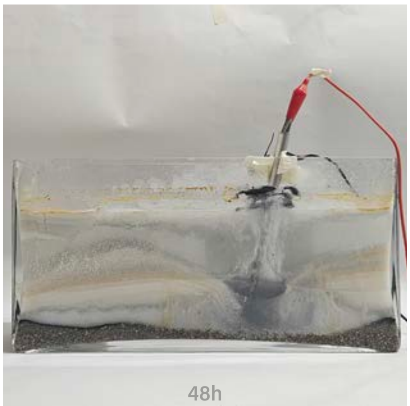
Masking Tape

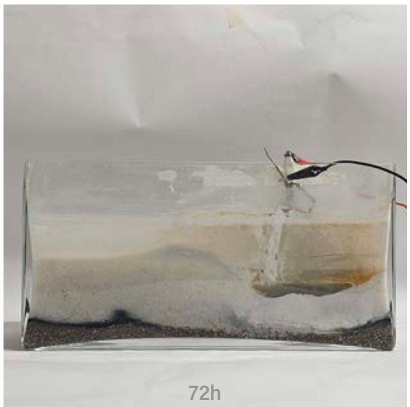
Lab Diary

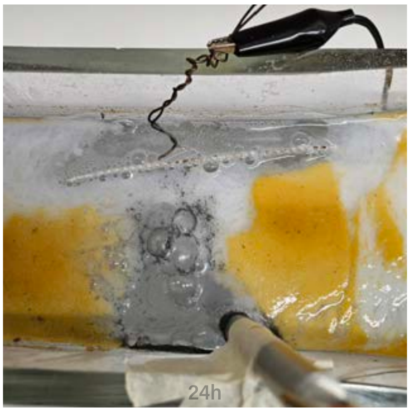
LAB	Lab 1	Lab 2
Working Time	2024.10.07 - 2024.10.18	2024.10.19 - 2024.10.26
Drying Time	2024.10.18 - 2024.10.19	2024.10.26 - 2024.10.27
Extra Operations in the Steps	▪ Connected to power for 8 hours daily for 3 days to ensure sufficient electrolysis for 24 hours. ▪ Changed aluminium rod after 48h because of its consumption and corrosion during the process, affecting the efficiency of mineral accretion.	▪ Cleaned the aquarium with sandpaper owing to the white deposits attached to its inner surface. ▪ Created different shapes of wire mesh to test if the forms would affect deposition efficiency and adhesion. ▪ Used fresh water to clean the seasand twice. ▪ Kept the power supply constant for 24 hours a day. ▪ Replaced the aluminium rod according to its consumption conditions.
Findings	**Metal Rod Consumption:** The aluminium rod was heavily corroded and consumed during the electrolysis with time. **Wire Mesh Corrosion:** A large area of corrosion appeared on the wire mesh owing to the discontinuous power supply. **White Deposit:** The white deposit increased after each cycle. When the powder was off overnight, the white substance settled at the bottom. **Yellow and Black Substance:** Some yellow and black substances showed up during the electrolysis, which was caused by the corrosion of the metal rod or steel wire mesh or the impurity of the metal rod.	**Shape Influence:** Curved mesh had more deposits than the straight one. **Deposition Pattern:** More white deposits were accumulated in the curved mesh, where the curvature was greatest. More deposition is closer to the metal rod, and more accumulation at the bottom because of gravity. **Deposited Material Loss:** The deposits accumulated on the wire mesh were depleted when taken out for observation and then submerged back due to the force of seawater impact. **Fragile White Deposits:** After drying out, the white substances on the wire mesh were fragile, more like white powder or particles instead of the limestone expected.
Improvement for next Labs	**Constant Power Supply:** Kept the power supply on for a consistent chemical reaction and to prevent wire mesh corrosion. **Replaced Metal Rod:** Changed the aluminium rod to a new one when heavily consumed to ensure efficient electrolysis. **Replenished Seawater:** Added the seawater during the process to ensure enough ions were present for mineral accretion.	**Changed Seawater:** Used artificial seawater instead of natural seawater to increase the calcium ion concentration, which might help deposit more. **Replaced Anode Material:** Changed the anode aluminium metal rod into the carbon rod that would not be reacted and consumed during the seawater electrolysis. Also, it would not create extra white flocculent like what the aluminium rod had done. **Reduced the Voltage:** According to Goreau (2012), lowering the voltage and current would increase the deposition efficiency.

Lab 1


24h


48h

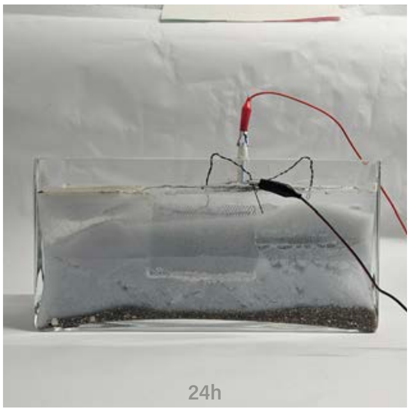

72h

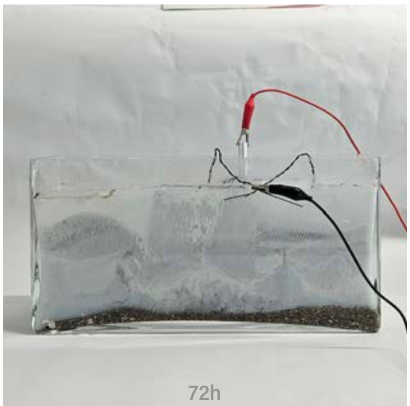

24h

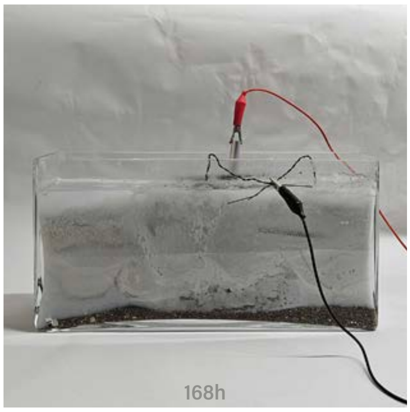

48h


72h

Lab 2

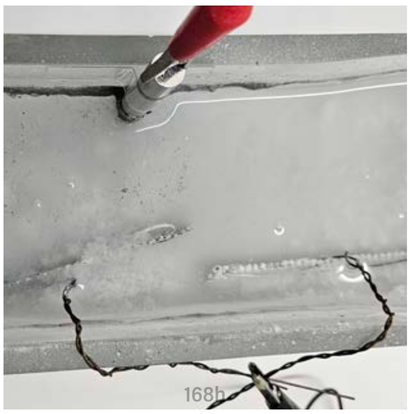

24h


72h


168h


24h

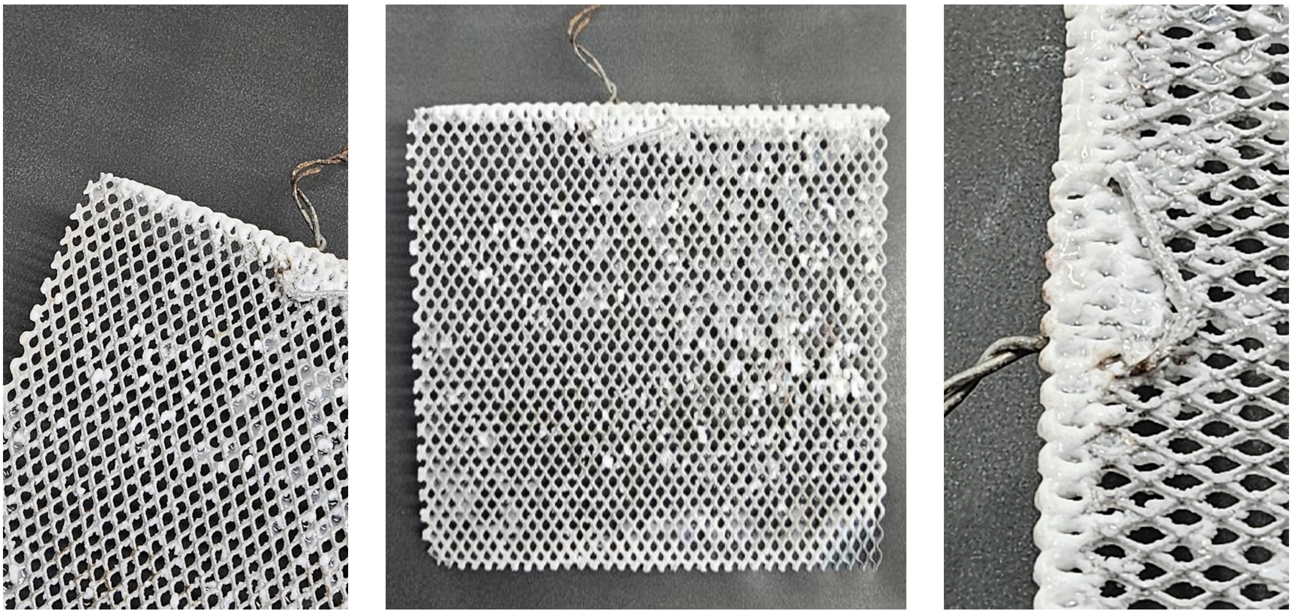

72h


168h

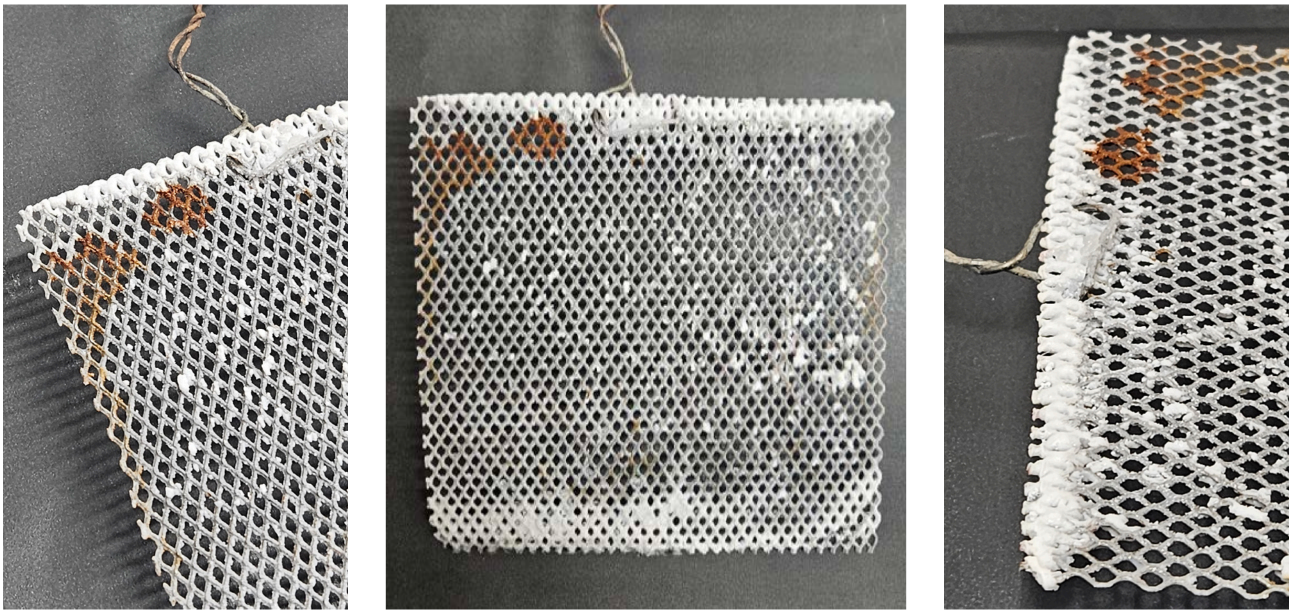
Sample

Lab 1

2024.10.07 - 2024.10.19



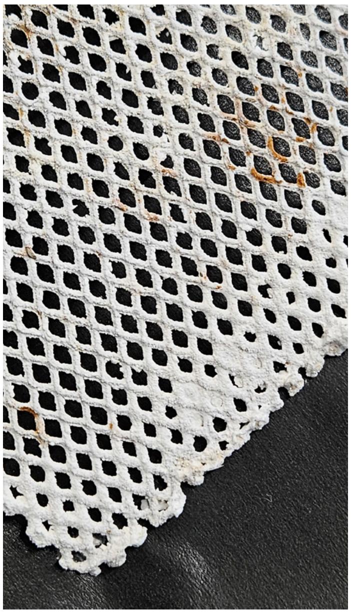
Sample after 24h of electrolysis



Sample after 48h of electrolysis



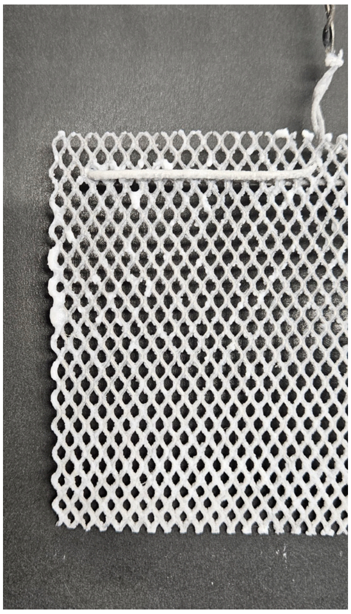
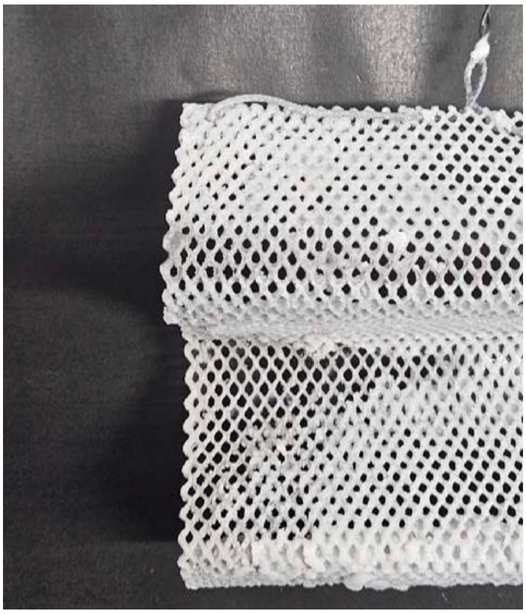
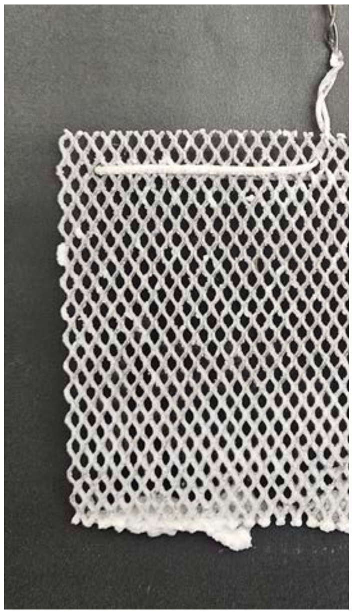
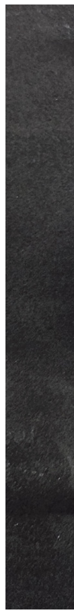
Sample after 72h of electrolysis



Sample after 72h of electrolysis and 24h of drying

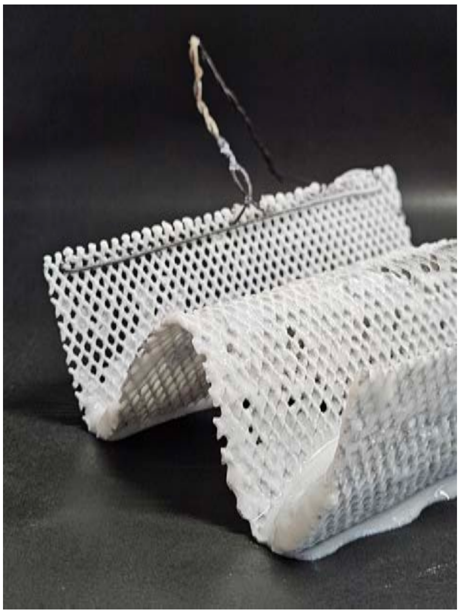
Lab 2

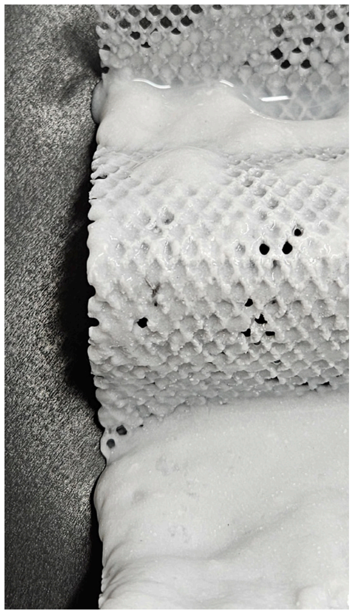
2024.10.19 - 2024.10.27

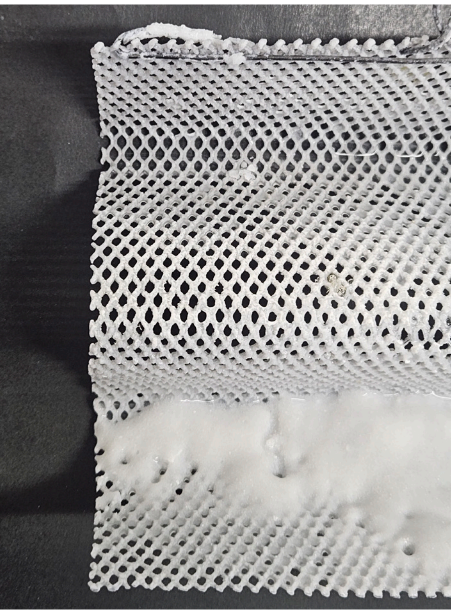
Sample after 24h of electrolysis

Sample after 48

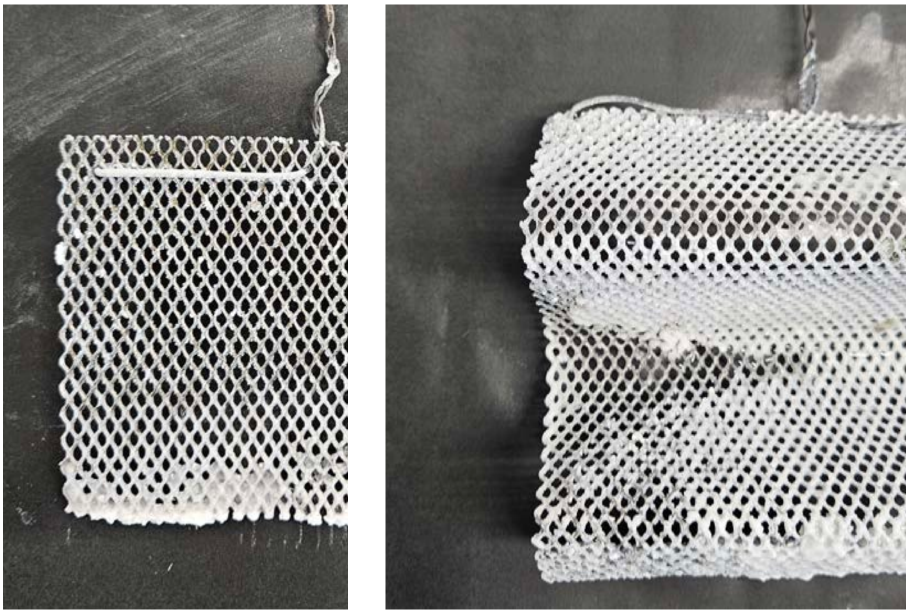




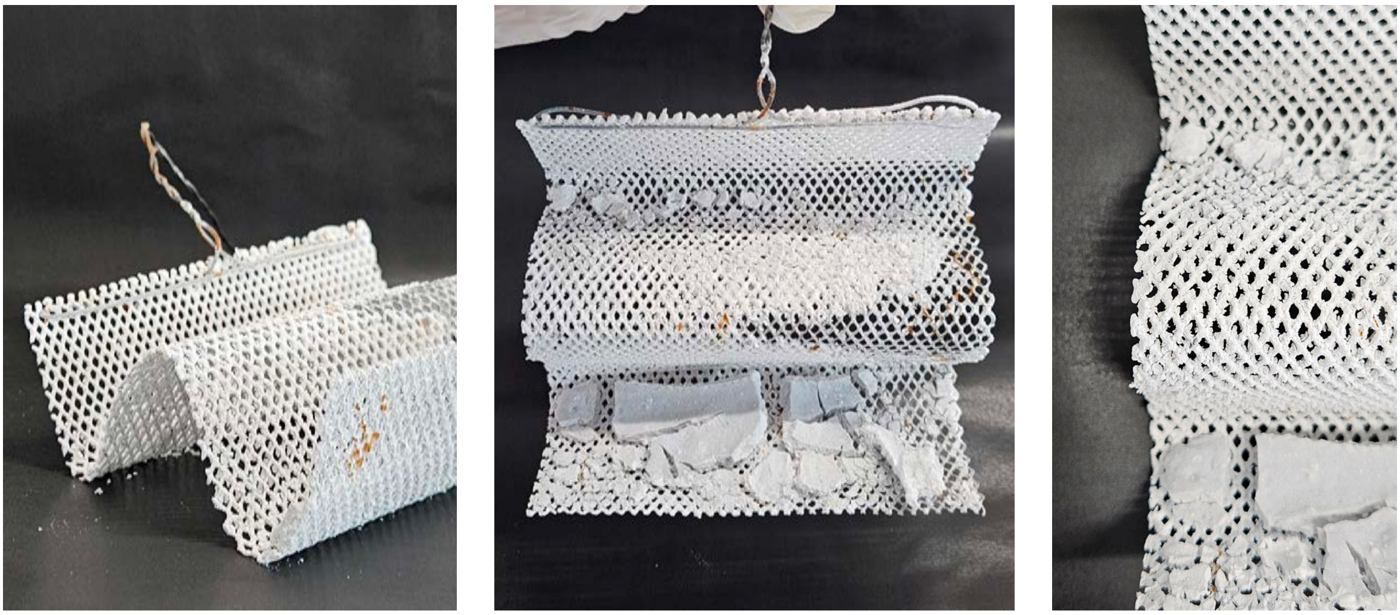
Sample after 1 week (168h) of electrolysis



h of electrolysis



Sample after 72h of electrolysis

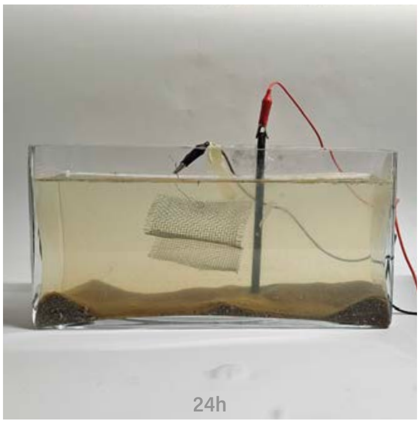


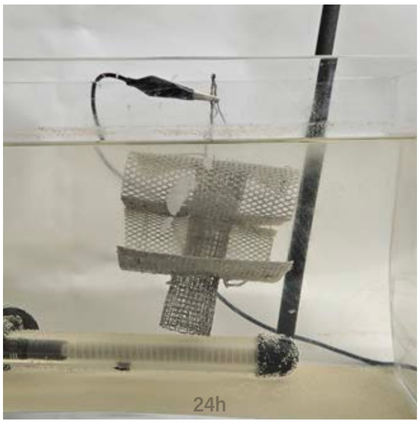
Sample after 1 week (168h) of electrolysis and 24h of drying

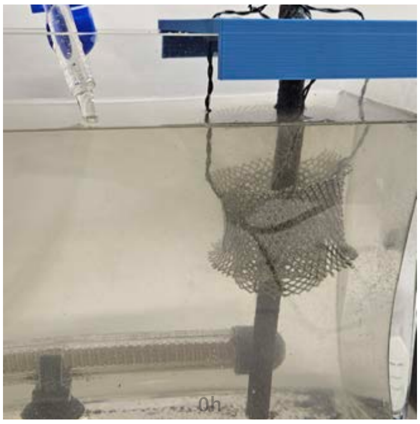
Lab Diary

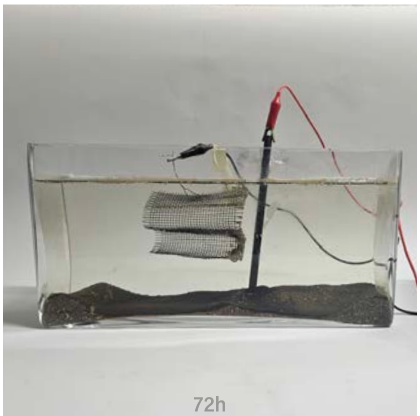
LAB	Lab 3	Lab 4	Lab 5
Working Time	2025.01.26 - 2025.02.01	2025.02.10 - 2025.03.10	2025.03.25 - 2025.04.01
Drying Time	2025.02.01 - 2025.02.02	2025.03.10 - 2025.03.11	2025.04.01 - 2025.04.02
Extra Operations in the Steps	▪ Cleaned the aquarium with sandpaper owing to the white deposits attached to its inner surface. ▪ Used fresh water to clean the seasand twice.	▪ Used two types of wire mesh with different forms, assembled with metal wires. The central cylinder was prone to corrode.	▪ 3D printed an object for holding wires and metal rods. ▪ Installed water pump for better deposition efficiency.
Findings	**Clear Seawater Environment:** After replacing the aluminium rod with the carbon rod, the seawater remained clear during the process. **Harder White Deposit:** In the places close to the carbon rod, white deposits, which look more like limestone, grew similar to those shown in the literature studies, and they were much harder and stronger. **Wire Mesh Corrosion:** The wire mesh used in Lab 3 was changed to another type prone to corrosion. The parts without the growth of white sediment soon rusted throughout the reaction process. **Black Substance:** Some black substances, more like particles or powders, appeared and attached to the surface of white deposition, likely caused by the impurity of the carbon rod.	**Deposition Pattern:** White sediments would first accumulate on the wire connected to the cathode directly, then grow on the parts close to the carbon rod and keep depositing on these parts. **More Base Deposition:** After some white deposits accumulate on the bottom, likely due to the impact of gravity, they grow more and more from the bottom upwards. **Cracks after Drying:** The grown white surface cracked slightly after drying, especially in the parts that adhered to more black carbon particles.	**More Even Deposits:** After placing the carbon rod in the centre, more even sediments grew in the wire meshes. **Black Surface:** Supposed to be white, the deposits were adhesion by the massive black particles due to the impurity of the carbon rod. **Core-Focused Deposition:** The open cylinder shape, closer to the centre, had more deposits. Also, the bottom parts of both shapes got more sediments due to gravity.
Improvement for next Labs	**Increased water temperature:** Warm temperature could help the growing efficiency, and it would also be better to simulate the seawater condition of the design site, Maldives. **Tested Complex Shape:** Explored two wire meshes with different forms, which were tied up with metal wires, to find and test the prototype of the design proposal.	**Relocated Carbon Rod:** Changed the carbon rod into the centre of the wire mesh's geometry to get more even growth. **Inserted Water Pump:** Used water pump to simulate the wave while keeping the ions in the seawater to move, aiming for better deposition efficiency. **Tested Design Prototype:** Created two shapes with the centres to be inserted with the carbon rod to test the growing pattern.	**Replaced High-Pure Carbon Rod:** Used more pure carbon rods for better growth efficiency and perfect outcomes. **Improve Growth Evenness:** Placed the carbon rods closed to the wire mesh, and more than one could be tied with wires and used simultaneously.

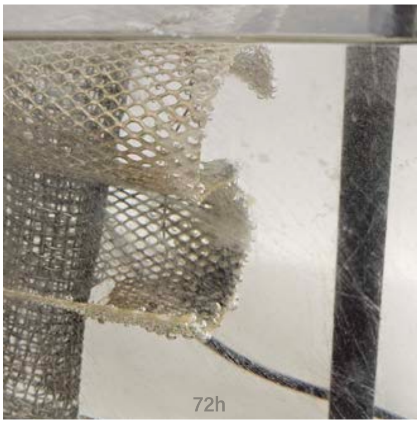
Lab 3 | **Lab 4** | **Lab 5**

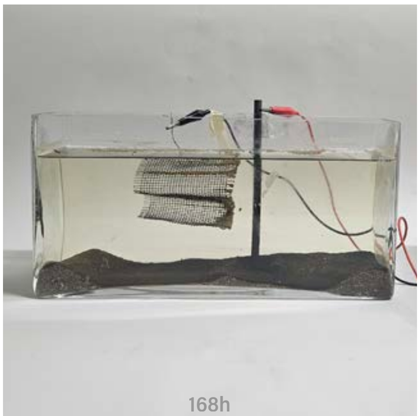


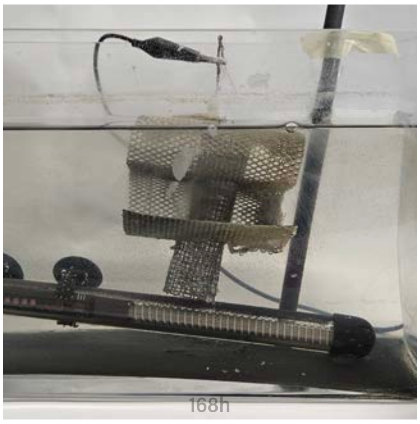


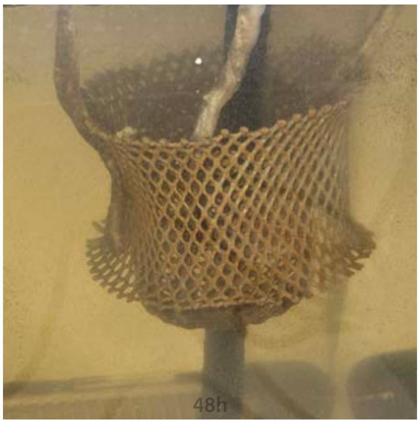


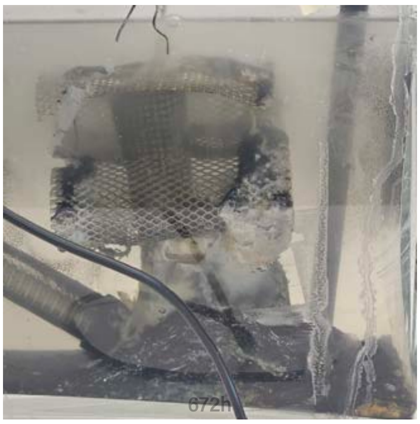


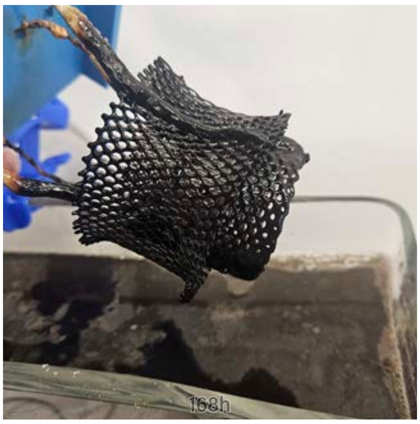








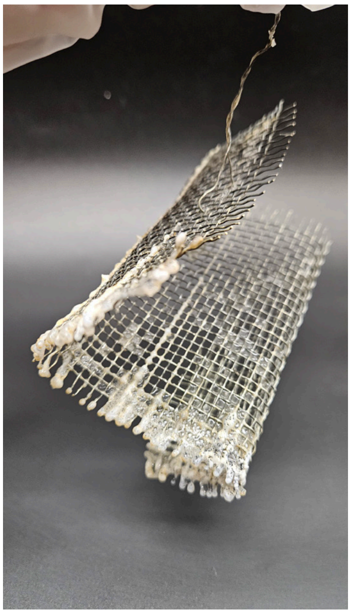
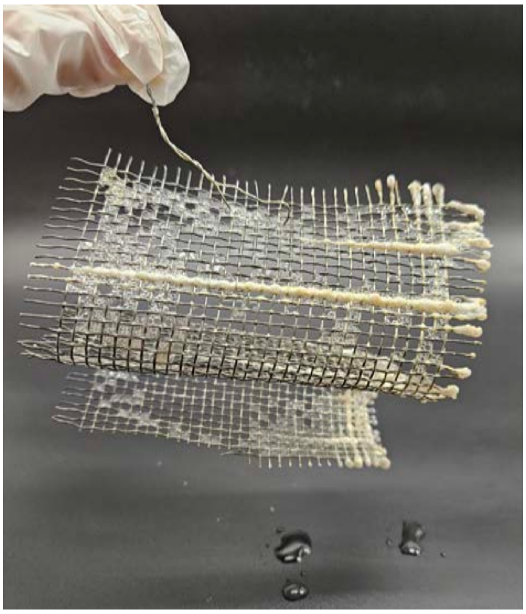
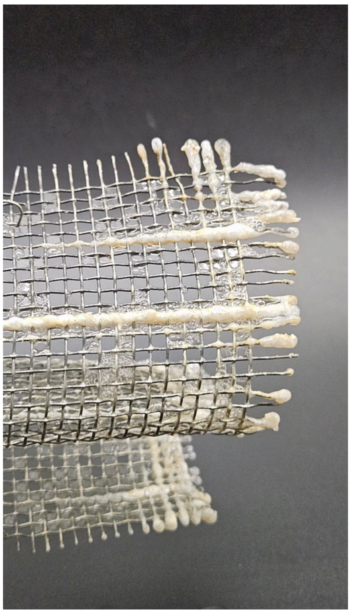




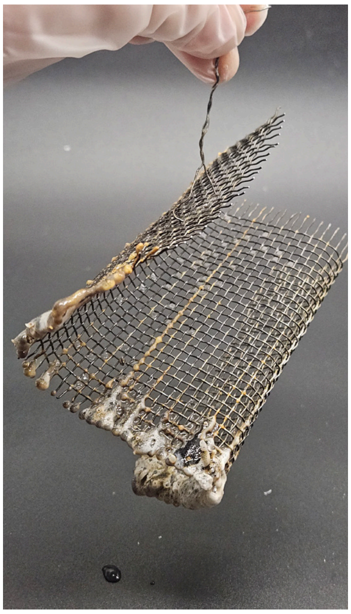
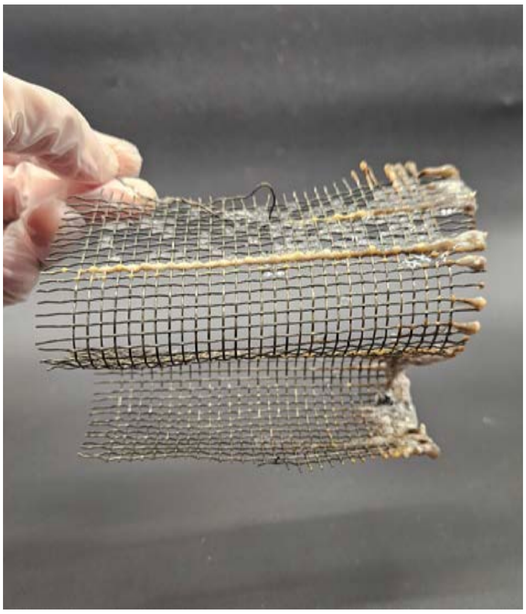
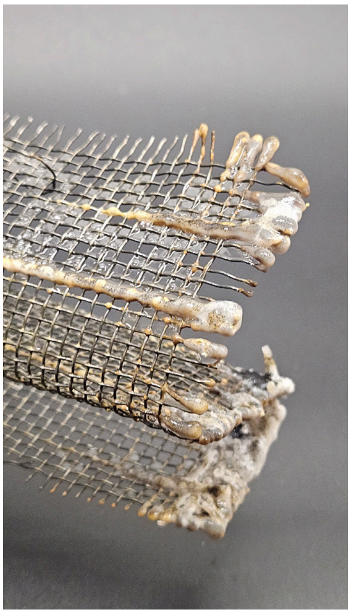
Sample

Lab 3

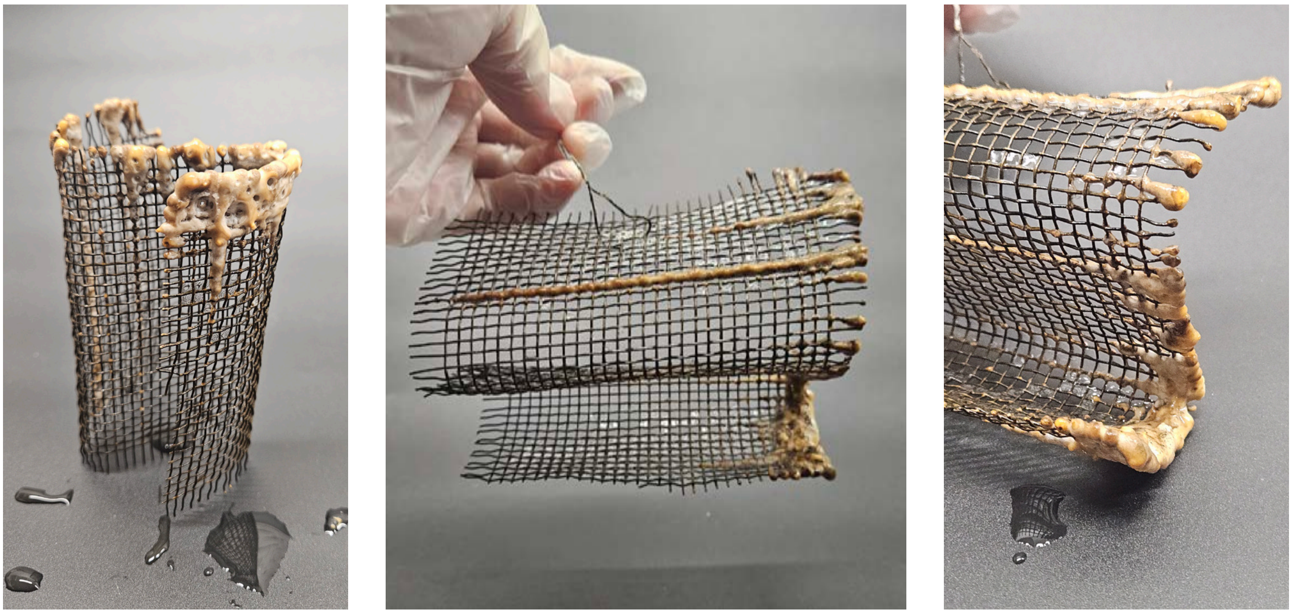
2025.01.26 - 2025.02.02

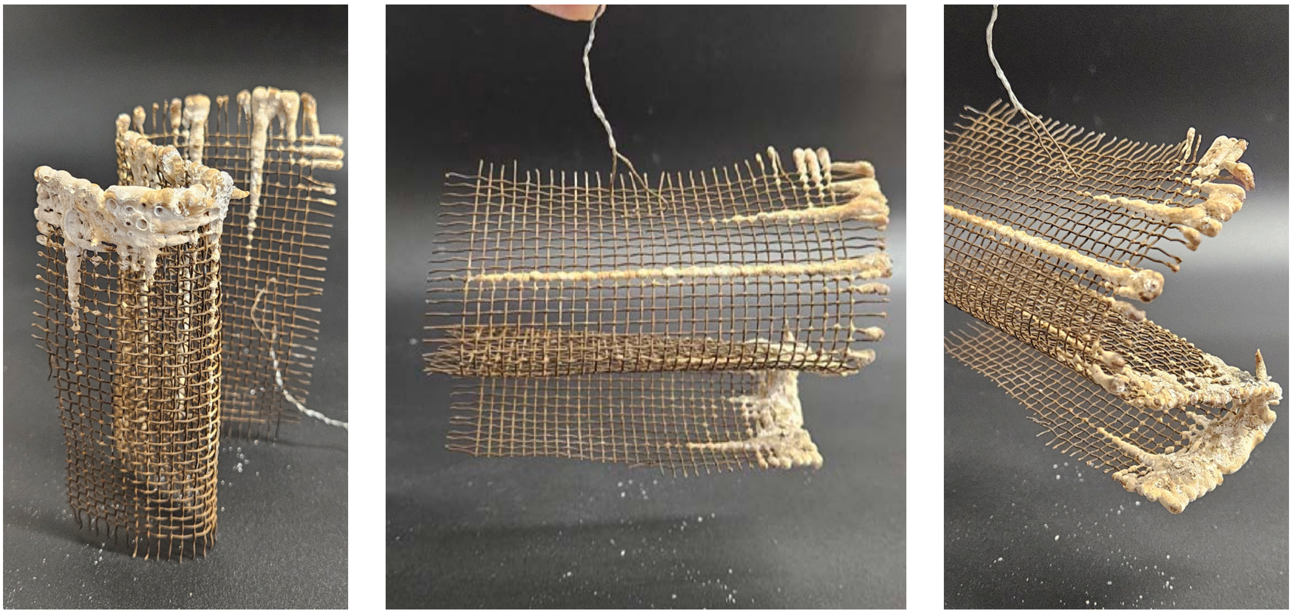
Sample after 24h of electrolysis

Sample after 72h of electrolysis



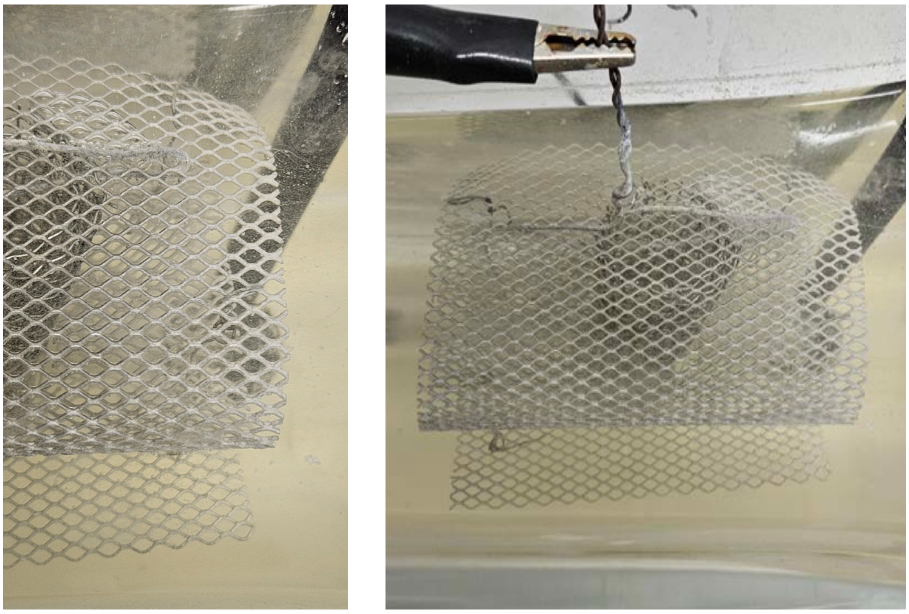
Sample after 168h of electrolysis



Sample after 168h of electrolysis and 24h of drying

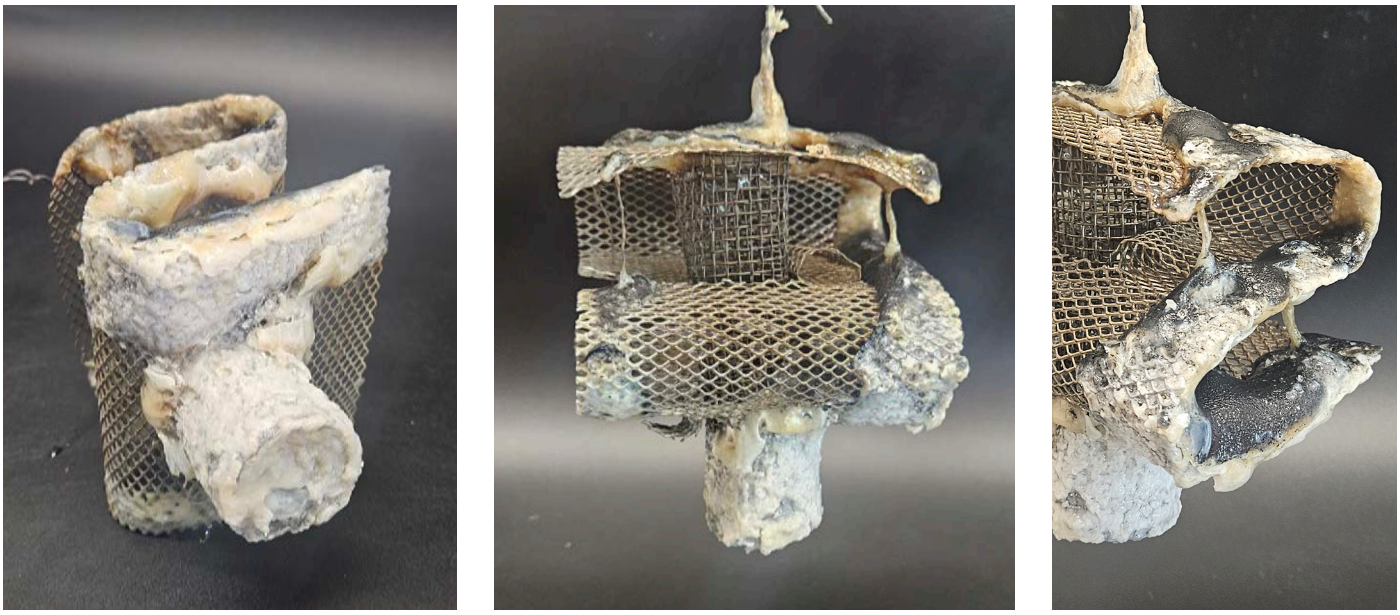
Lab 4

2025.02.10 - 2025.03.11

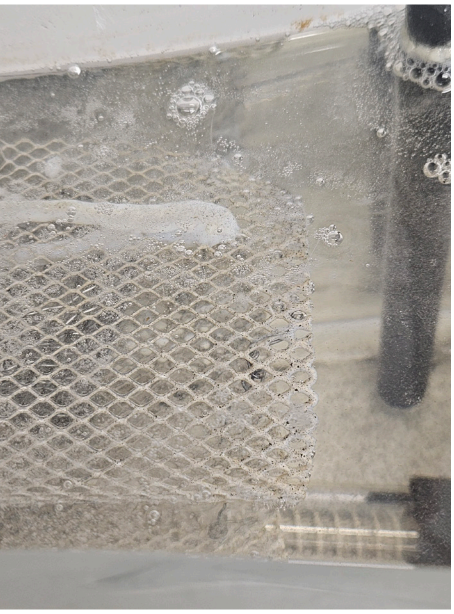


Sample after 24h of electrolysis

Sample after 48

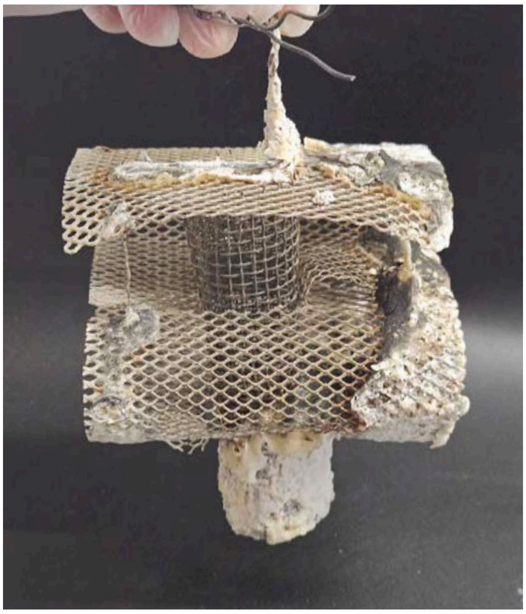


Sample after 672h of electrolysis



h of electrolysis

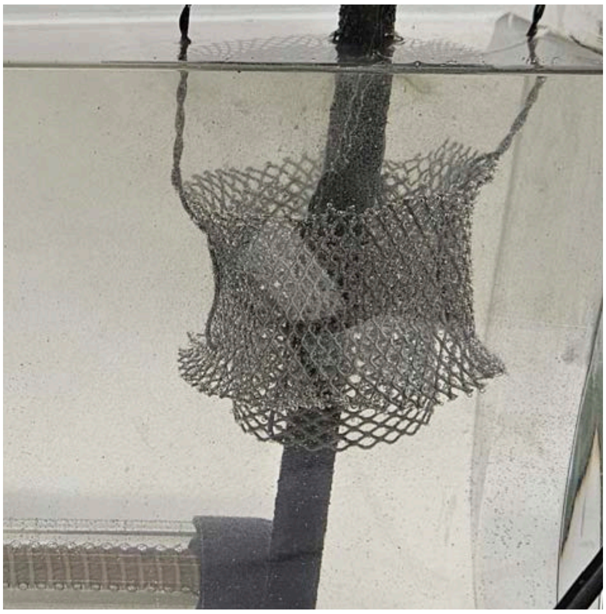
Sample after 1 week (168h) of electrolysis



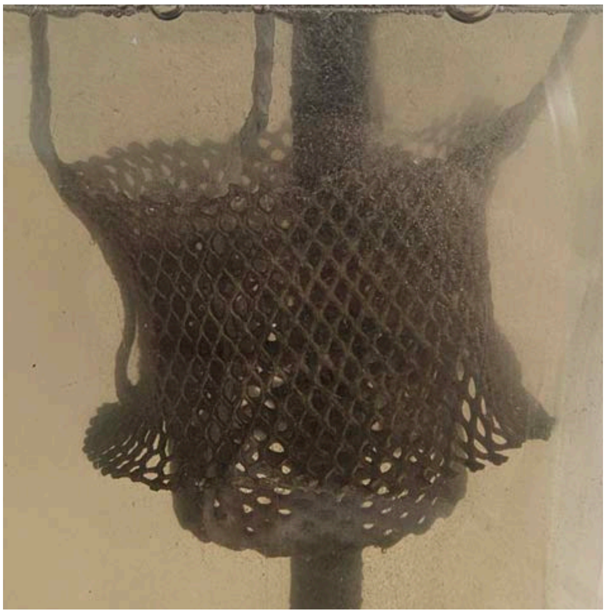
Sample after 672h of electrolysis and 24h of drying

Lab 5

2025.03.25 - 2025.04.02



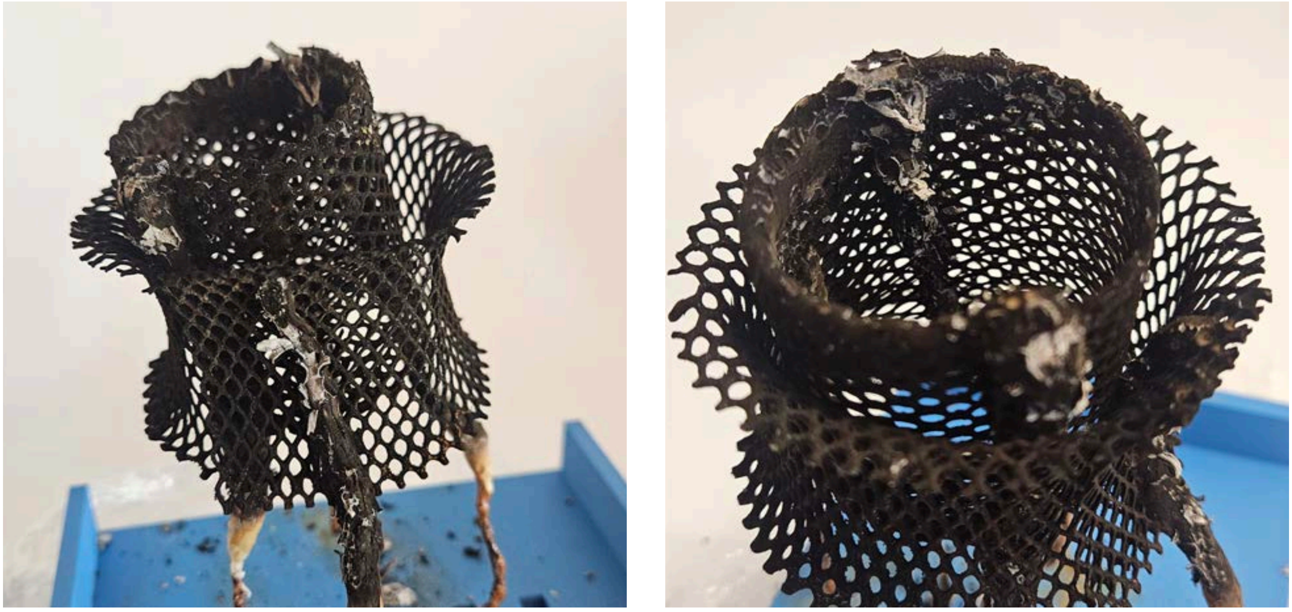
Sample after 0h of electrolysis



Sample after 24h of electrolysis

Sample after 48h of electrolysis

Sample after 168h of electrolysis



Sample after 168h of electrolysis and 24h of drying

Samples in two shapes

Observation

- **Yellow substance appearance**

  Theoretically, the experiment should not show any yellow substance. Why are there yellow deposits? The reasons are as follows:

  a. At first, there was no current passing through. One steel wire was used as anode material for a while to test if there was any current or not. After a while, the water turned yellow. Steel is primarily an alloy of iron and other elements, so when an electric current passes through it, trivalent iron ions are produced, which makes the water yellow.
  b. Steel wire mesh contains the iron element which was then be passed through the current and produced iron ions causing the water to turn yellow. Hydroxide ions are produced when the water is energized (Goreau, T. J, 2012), and the yellow substance produced may be iron hydroxide formed by the combination of iron ions and hydroxide ions.

- **White Deposit (Limestone and Brucite)**

  According to Goreau, T. J (2012), some reactions in both anode and cathode contribute to the white deposits. Here are the he chemical formula for the reactions:

  Anode:

  $$H^+ + CaCO_3 = Ca^{2+} + HCO_3^-$$

  Cathode:

  $$Ca^{2+} + HCO_3^- + OH^- = CaCO_3\downarrow + H_2O$$

  According to the chemical formula above, calcium carbonate deposits, which are limestone, are produced on the wire mesh of the cathode. However, when the higher density current passes through the cathode, it increases the concentration of hydroxide ions, which leads to side reactions:

  Cathode:

  $$Mg^{2+} + 2OH^- = Mg(OH)_2\downarrow$$

  This results in the production of the sediment of magnesium hydroxide, also known as brucite, which is a white mineral similar to limestone but with a weaker structure and is flaky. Interestingly, brucite ($Mg(OH)_2$) can be converted into magnesium carbonate by absorbing carbon dioxide, which is stronger than limestone ($CaCO_3$).

  $$Mg(OH)_2 + CO_2 = MgCO_3 + H_2O$$

- **White Flocculent (Al(OH)3)**

  Aluminium is an amphoteric oxide that dissolves easily in both acidic and alkaline conditions (Goreau, T. J, 2012). The material used for the anode in Lab 1 and Lab2 is an aluminium rod, which reacts with hydroxide ions to form a white flocculent - aluminium hydroxide ($Al(OH)_3$).

  $$Al^{3+} + 3OH^- = Al(OH)_3\downarrow$$

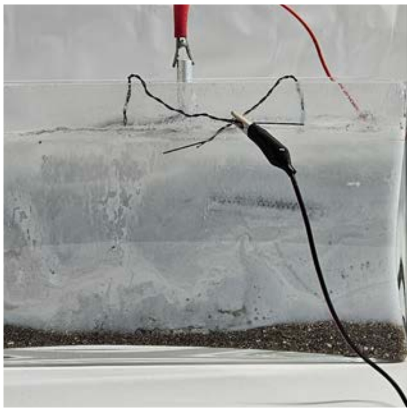
  This flocculent can be attached to the wire mesh, which is looser than calcium carbonate and magnesium hydroxide.












- **Black Substance**

  In the labs using carbon rods as anode material, the samples are all white deposits based on and attached to black substances, and they even cover the surface of lab 5. Moreover, these black particles appeared more near the carbon rod. After consulting with Guokang Li, a master's student in Material Engineering at Chalmers, the reason for this situation was that the carbon rods were not pure, which would dissolve and give off the black particles when the electrolysis happened. These black particles then adhered to the white-grown material, influencing both the growth efficiency and aesthetic appearance.

- **Bubbles generation**

  Seawater contains nine main elements, which are chlorine, sodium, magnesium, sulfur, calcium, potassium, bromine, carbon, and strontium (Hilbertz, W.,1979). Since this experiment was tested with seawater, when an electric current was passed through, oxygen and chlorine were produced at the positive electrode and hydrogen at the negative electrode (Hilbertz, W.,1991). Therefore, the bubbles that appeared during this experiment were these gases.

  Anode:

  $$2H_2O = O_2\uparrow + 4H^+ + 4e^-$$

  $$2Cl^- = Cl_2\uparrow + 2e^-$$

  Cathode:

  $$4H_2O + 4e^- = 2H_2\uparrow + 4OH^-$$

- **Anode Metal Rod Consumption**

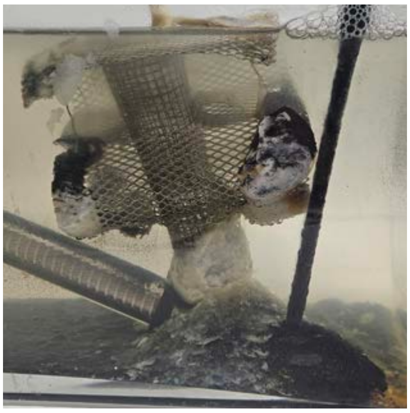
  All the labs showed that the anode metal rod would be consumed heavily over time. However, the reasons leading to this were completely different. For labs 1 and 2, the metal rod was aluminium, which would react heavily with hydroxide ions in the seawater during the biorock accretion process using electricity. This process means that the aluminium rod would dissolve and consume within time.

  a. For labs 1 and 2, the metal rod was aluminium, which would react heavily with hydroxide ions in the seawater during the biorock accretion process using electricity. This means that the aluminium rod will dissolve and consume itself within a certain time, as shown in the images on the right.

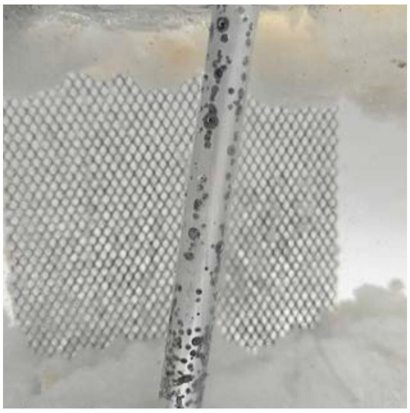
  b. For labs 3-5, the carbon rod, an inert conductive material, was used because of its high chemical stability to conduct current without reacting with ions in the seawater. Theoretically, it would not dissolve or consume like what the aluminium rod had done. However, it did dissolve and consume actively, with the black particles or powders appearing in the water and attaching to the white deposits, which affected the aesthetic and visual properties of the samples. The reason for this might be the impurity of the carbon rods.

- **Wire Mesh Corrosion**

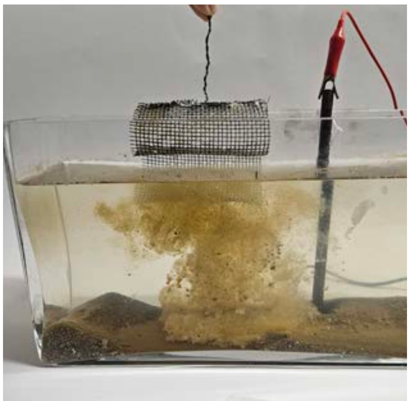
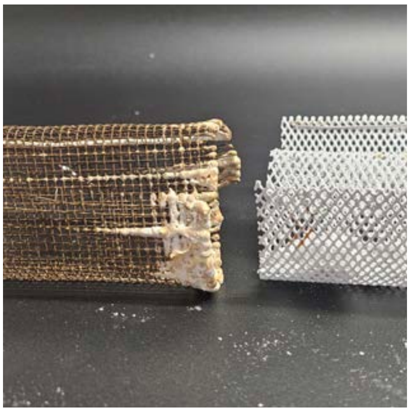
  The steel wire mesh would be rusted owing to the chemical reaction between the iron ions and ions in the seawater, which corroded while producing the yellow substances. The wire mesh would rust rapidly and seriously influence deposition efficiency, especially when raising the voltage, as in lab 3's trial experiment (see the images on the right).



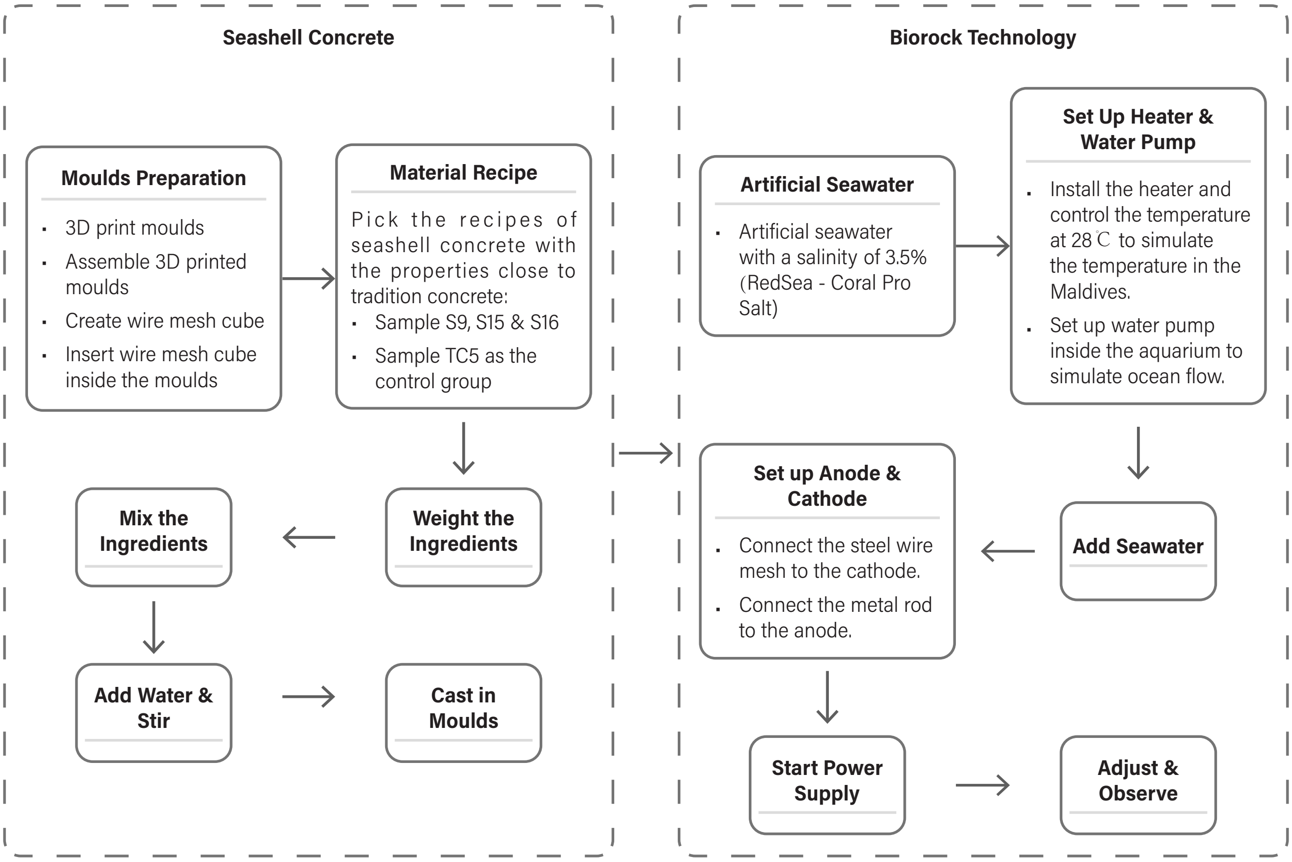





Experiment 4 - Hybrid Material

Steps

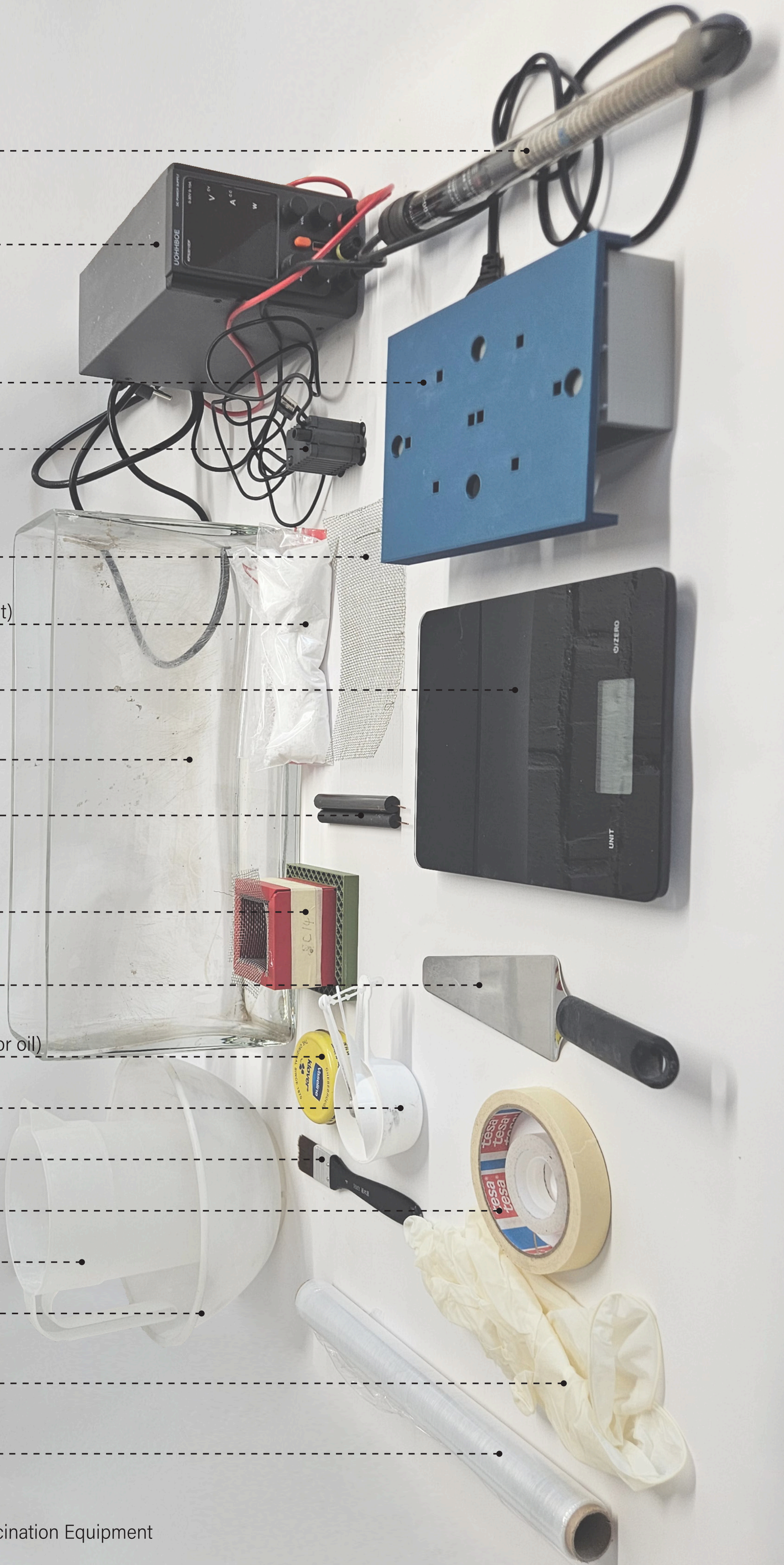


Recipe

Lab	Sample	Size (cm×cm)	Fine Aggragates (g)	Coarse Aggragates (g)	Seashell Powder (g)	Clay (g)	Steel Slag Ash (g)	Gypsum (g)	W/SP	Metal Rod Type	Metal Rod Size (cm×mm)	Time Use Hour (h)	Direct Current Voltage (V)
Lab 1	H1	5×5×5	104.68	122.58	63.56	0	0	0	0.86	Carbon	30×12	672	3.5
	H2		104.68	122.58	63.56 (100%)	0	0	0					
	H3		104.68	122.58	41.32 (65%)	3.18 (5%)	15.90 (25%)	3.18 (5%)					
	H4		104.68	122.58	47.67 (75%)	9.54 (15%)	3.18 (5%)						

The recipe for H1 is from TC5, H2 is from SC9, H3 is from SC15, and H4 is from SC16. Because of the time limitation, the hybrid material lab only has one, so if the time is enough, it would be better to explore more based on the findings from lab 1.

Tools



Thermostatic Heater

DC Powder Supplyment

Moulds for Fixing

Small Water Pump

Steel Wire Mesh

Seasalt (RedSea-Coral Pro Salt)

Kitchen Scale

Aquarium

Carbon Rod

Moulds for Casting

Trowel

Coating (petroleum jelly, wax or oil)

Measuring Spoons

Brushes

Tape

Measuring Cup

Container for Mixing

Gloves

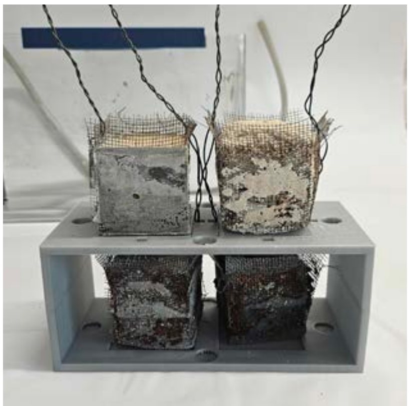
Cling Film

Orthers: Saucepan, Oven, Calcination Equipment

Lab Diary

LAB	Lab 1
Working Time	2025.04.10 - 2025.04.14
Curing Time	2025.04.14 - 2024.05.18
Extra Operations in the Steps	▪ Poured the paste into the mould layer by layer and vibrated sufficiently. ▪ Placed a weight over the moulds and compacted them. ▪ After the samples solidified in the air for 96 hours, they were removed from the moulds and placed in the seawater for biorock accretion. ▪ 3D printed moulds for fixing the carbon rod, wires and seashell samples. ▪ A heater and water pump were supposed to be used, simulating the design site's temperature and ocean wave and increasing the deposition efficiency and ions movements. However, the size of the heater could not fit in when there was a 3D-printed mould, and the water pump could not work for no reason.
Findings	**Surface Texture:** After demoulding, the surface texture of the samples with the seashell was rougher than that of the one made by the traditional concrete. Moreover, the seashell concrete samples had exposed more areas of steel wire mesh, some of which were seriously corroded, and the sample with more steel slag ash had more severe corrosion. **Deposition Pattern:** Similar to the findings in the Biorock Experiment (experiment 3), the deposition started from the parts connected to the cathode directly and the places close to the carbon rods. Moreover, it happened more on the exposed wire mesh parts. **More White Deposits:** Compared to the Biorock Experiment, this hybrid material test produced more and thicker white deposits. Moreover, samples with seashell concrete had more white deposits, which might be caused by the chemical reactions within the seashell concrete during the seawater electrolysis. The main composition of seashell concrete is calcium carbonate, which will release calcium and carbonate ions during seawater electrolysis that promote mineral accretion in the biorock experiment. **Protected Mineral Coating:** The exposed wire mesh, especially the places that rusted severely, was coated with these mineral sediments, showcasing that it could be self-repairing.
Improvement for next Labs	**Replace the Wire Mesh:** Try to use stainless wire mesh to reduce the corrosion situation. **Simulate the Marine Environment:** To ensure the feasibility of using this hybrid material at the design site, use a heater and a water pump to simulate the temperature and waves of the ocean in the Maldives. **Add Carbon Rods:** Add carbon rods to each side of the seashell concrete cube to make sure the biorock can grow more evenly.

Seashell Concrete



Biorock




Sample

Cured Sample | **Dry Sample**

HM1

Appearance

Workability

Density

Porosity

Water Absorption

HM2

Appearance

Workability

Density

Porosity

Water Absorption

HM3

Appearance

Workability

Density

Porosity

Water Absorption

HM4

Appearance

Workability

Density

Porosity

Water Absorption

NOTE: Detailed data comparisons are provided on Page 49.

Material Evaluation

Material	LAB	Sample	Dimension-Before (cm)	Dimension-After (cm)	Shrinkage (%)	Wor
Concrete	LAB1	TC1	10×10×10	10×10×9.9	1	I
		TC2	10×10×2	10×10×2	0	G
	LAB2	TC3	5×5×5	5×5×5	0	G
	LAB3	TC4	5×5×5	5×5×4.8	4	G
		TC5		5×5×5	0	G
Seashell Concrete	LAB1	SC1	10×10×10	10×9.9×9	10	F
		SC2	10×10×2	10×10×2	0	F
	LAB2	SC3	5×5×5	5×5×4.7	6	I
		SC4		4.9×4.9×4.8	4	F
		SC5		5×5×5	0	F
		SC6		5×5×4.9	2	F
		SC7		5×5×5	0	I
		SC8		5×5×4.9	2	F
	LAB3	SC9	5×5×5	5×5×5.2	-4	I
		SC10		5×5×5.3	-6	I
		SC11		5×5×5.1	-2	I
		SC12		5×5×5	0	I
		SC13		5×5×5.2	-4	I
		SC14		5×5×5.1	-2	I
		SC15		5×5×5.1	-2	I
		SC16		5×5×5.1	-2	I
Hybrid Material	LAB1	HM1	5×5×5	5×5×5	0	I
		HM2		4.8×4.8×5	4	I
		HM3		5×5×5	0	I
		HM4		4.8×4.7×5	6	I

kability	Porosity (%)	Weight (g)	Density (g/cm3)	Weight after Submersion (g)	Water Absorption (%)
Fair	11.21	2263	2.29	2374	4.68
Good	14.00	459	2.30	487	5.75
Good	12.00	294	2.35	309	4.85
Good	1.67	279	2.33	281	0.71
Good	0.80	306	2.45	307	0.33
Poor	32.55	1376	1.54	1666	17.41
Poor	30.50	293	1.47	354	17.23
Fair	25.53	201	1.71	231	12.99
Poor	13.02	210	1.82	225	6.67
Poor	21.44	219	1.81	245	10.61
Poor	22.40	229	1.83	257	10.89
Fair	18.65	230	1.87	253	9.09
Poor	22.46	217	1.87	243	10.70
Fair	7.69	248	1.91	258	3.88
Fair	7.55	249	1.88	259	3.86
Fair	9.41	261	2.05	273	4.40
Fair	9.60	255	2.04	267	4.49
Fair	10.77	266	2.05	280	5.00
Fair	8.63	263	2.06	274	4.01
Fair	7.84	268	2.10	278	3.60
Fair	3.92	264	2.07	269	1.86
Fair	5.60	307	2.46	314	2.23
Fair	42.53	256	2.22	305	16.07
Fair	24.80	253	2.02	284	10.92
Fair	23.94	250	2.22	277	9.75

AI USE

ChatGPT

- Brainstorms: I used it for inspiring ideas and research directions about the topic when I did not know what to do at the beginning.
- Reference searching: I used it to find projects, case studies, and theories related to my topic. Moreover, I used it to extract some keywords for my search in the database for academic articles.
- "Answer Book": I sometimes used it as the guidebook when I encountered difficulties with program problems. For example, when I did not know how to build some crazy shapes or how to deal with the data tree and data in Grasshopper, how to generate the content automatically in InDesign, and many other problems similar to these.
- Text Prompts: I used it to modify and optimize my text prompts, which would be used in Midjourney for inspiration about my design and some logos or cover page images.

Midjourney

As a helpful inspiration tool for many designers, Midjourney was used to generate some abstract and aesthetic images for the cover page and title page. I also used it for design concept inspiration, which served as one of the prototypes of my design form.

Grammarly

I used Grammarly to check my grammar and improve my expression.


BLUE PLANET