REUSE THE CERAMIC GLAZED TILE WASTE FOR THE DEVELOPMENT OF MARINE CONCRETE MODULAR

Samudika Umayanga Liyanage

(208016V)

Degree of Master of Science

Department of Civil Engineering

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Thesis Submitted in Partial Fulfillment of the Requirements for the Degree

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DECLARATION

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Name of the Supervisor: Prof. R.U. Halwatura

Signature of the supervisor: Date: 10/03/2025

Name of the Supervisor: Prof. Terney Pradeep kumara

Signature of the supervisor: Date: 10/03/2025

ABSTRACT

Coral reefs are critical to marine ecosystems, offering essential services such as coastal protection, food security, and habitats for diverse marine life. Despite their importance, these ecosystems are rapidly degrading due to environmental stressors and human activities. This study addresses coral reef degradation by developing an eco-friendly, sustainable solution using ceramic tile waste in concrete modular designs to support coral regrowth. The primary objectives were to study Sri Lanka's coastal marine environment, assess the feasibility of reusing ceramic tile waste, and develop an optimized concrete mix for marine conservation structures.

The methodology included an extensive literature review on coral transplantation, the role of concrete structures in marine conservation, and ceramic tile waste as an alternative material. Laboratory experiments explored the use of ceramic tile waste as a partial replacement for fine aggregates at proportions of 25%, 50%, 75%, and 100%. Key tests—such as sieve analysis, slump tests, compressive strength tests, and X-ray diffraction (XRD)—validated the safety and suitability of ceramic waste for marine environments. Field deployment of two modular designs, Coral Hab and Marine Condo, at Polhena Beach, Sri Lanka, monitored coral growth and marine biodiversity. Results indicated that the optimal mix was achieved with a 25% replacement of fine aggregates using ceramic tile waste, providing structural integrity, environmental compatibility, and the required strength of 25 MPa. Incorporating foam concrete emerged as the most effective method, with 26% foam content identified as the optimal composition for cost efficiency, weight reduction, and improved surface quality.

XRD tests confirmed the absence of harmful substances in the ceramic waste. Following this, additional efforts focused on reducing weight, improving porosity, and lowering costs. Field results demonstrated that the concrete modules supported coral colonization and enhanced marine biodiversity. These findings confirm ceramic tile wastes and foam concrete's viability as sustainable materials for coral reef restoration. The study contributes to both marine conservation and sustainable waste management by repurposing ceramic tile waste into innovative reef restoration solutions. Further research is recommended to expand the application of these materials and assess long-term impacts on coral regrowth and marine ecosystems.

Keywords — Ceramic Tile Waste, Corals, Mix Designs, Marine Conservation, Foam Concrete, Waste Management.

DEDICATION

This Dissertation is dedicated to

My loving parents, my wife, my siblings, and my friends.

For their endless love, support, and encouragement given during this journey.

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Many people helped me out with this project. Professors Prof. R.U. Halwatura and Prof. P.B. Terney Pradeep Kumara gave me vital comments on my analysis and framing, replying to my emails at odd hours of the night and early in the morning. As I mentioned several other professors also, provided insightful comments.

I wish to thank Dr. L.L Ekanayake, Prof. Kumari Gamage, and Dr. Nimal Wijayaratnna of the progress review committee, fellow research assistants at Pro-Green Laboratory, Department of Civil Engineering, and University of Moratuwa in particular. I discovered most of the papers through their course on developing coral reforming structures, and they encouraged me to write this thesis, so I was certain that both the topic and my inquiry were worthy of each other.

Furthermore, I want to acknowledge the invaluable contributions of several colleagues who played a significant role in facilitating and supporting this study. Their assistance was important, and their collective efforts were crucial to the successful completion of this study.

Finally, I will always be grateful to my family for everything they have done for me. I devote everything to my loving family.

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Abbreviations	Description
CGTW	Ceramic Glazed Tile Waste
NFC	Natural Fiber Composites
CC	Climate Change
MCM	Marine Concrete Modular
GB	Green Building
GBCSL	Green Building Council of Sri Lanka
LCC	Life Cycle Cost
PCA	Principal Components Analysis
MPA	Marine Protected Area
MPW	Marine plastic waste
NARRDA	National Aquatic Resources Research and Development Agency
SDG	Sustainable Development Goal
WMA	Waste Management Authority
XRD	X-ray diffraction
MB	Marine Biological
MGE	Marine Geological environment

1 INTRODUCTION

1.1 Background

This marine habitat enjoys the salt, seagrass meadows, mangroves, mudflats, and coral reefs close to shore. While generating possibilities for tourism and pleasure, these marine systems influence the world's climate, water cycle, biodiversity, food chains, and energy supplies. Corals can occasionally be mistaken for aquatic vegetation or rocks. Corals cannot manufacture their nourishment as plants can, while being alive, unlike rocks. Animals include corals. Hundreds of thousands of tiny creatures called "Polyps," which are linked to sea anemones, make up a single coral branch. Reefs of coral refer to these large collections of coral. But these coral reefs are disappearing globally. In Sri Lanka, the southern region has been the center of the tourism business for the past 30 years. Additionally, most of the environmental harm occurs there. This has also affected corals. The southern beach's coral cover is eroding at an increasing rate. The focus on regrown corals is quite low in Sri Lanka, even though corals require optimum circumstances and an exceptionally extended period for their conservation. Since Sri Lanka's building market is developing and alternatives are being used for various reasons, including sustainability and economic viability, there is a great need for the sector. Additionally, Sri Lanka faces a genuine issue with ceramic tile waste. While the tile production facilities have been in operation all year, their capacity has expanded. The world's industrial and consuming regions are depicted in Figure 1.1. As evidenced, Asia has the largest ceramic consumption and production rates. As a result, there are many diverse types of waste produced during the production process. About 20 tons of rubbish are produced every day in the nation because of the disposal of tile waste, which consists of tile fragments and tile squares that cannot be utilized during this after-killing procedure. Ceramic trash has not received much attention in Sri Lanka. However, because ceramic stockpiles may last for at least 2000 years without degrading, it is becoming an environmental concern with long-term effects. Figure 1.2 provides a visual summary of World Tile production by geographical area in 2018.

WORLD MANUFACTURING AREAS			
AREAS	2018 (Sq.mt Mill.)	% on world production	% var. 18/17
EUROPEAN UNION (28)	1,366	10.4%	0.3%
OTHER EUROPE (Turkey included)	618	4.7%	0.5%
NORTH AMERICA (Mexico included)	348	2.7%	-3.9%
CENTRAL-SOUTH AMERICA	1,064	8.1%	-0.9%
ASIA	8,980	68.6%	-5.2%
AFRICA	718	5.5%	3.2%
OCEANIA	5	0.0%	0.0%
TOTAL	13,099	100.0%	-3.6%

WORLD CONSUMPTION AREAS			
AREAS	2018 (Sq.mt Mill.)	% on world consumption	% var. 18/17
EUROPEAN UNION (28)	1,034	8.1%	2.5%
OTHER EUROPE (Turkey included)	556	4.3%	-1.6%
NORTH AMERICA (Mexico included)	565	4.4%	-0.9%
CENTRAL-SOUTH AMERICA	1,168	9.1%	0.7%
ASIA	8,511	66.4%	-5.6%
AFRICA	930	7.3%	1.1%
OCEANIA	54	0.4%	1.9%
TOTAL	12,818	100.0%	-3.6%

Figure 1.1: World manufacturing and consumption areas

Source: (Ceramic World Review no. 138)

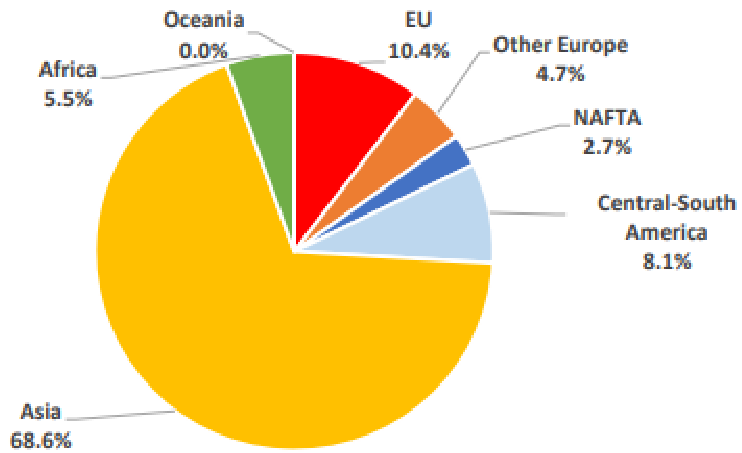


Figure 1.2: World Tile production by geographical area in 2018 - % shares

Source: (Ceramic World Review no. 138)

1.2 Problem Statement

Like most tropical islands, Sri Lanka is surrounded by beautiful beaches. And beneath the water is an extensive network of reefs, molded together by the skeletons of millions of tiny coral polyps. Over many millennia these tiny animals have shaped the underwater world around our island, building immense coral gardens that not only provide a home for a dazzling array of colorful reef fish and other underwater denizens but also helped shape our coastline by mitigating the impact of storm waves and providing safe anchorage for boats. Washed by the nutrient-rich currents of the Indian Ocean, Sri Lanka's reefs are high in biodiversity.

More than one hundred and ninety species of hard corals have been recorded within our waters while shore fish diversity is estimated to be more than nine hundred species. In addition, coral reefs are safe to house thousands of species of invertebrates such as soft corals, marine worms, slugs, and sea stars as well as marine turtles, and marine mammals. The northwest coast and the south coast of Sri Lanka are both synonymous with coral reefs. Off Kalpitiya, the Bar Reef constitutes what is perhaps the single largest reef system in the country. Vast areas of coral, mostly branching and table corals, provide refuge and feeding grounds for large schools of parrotfish, surgeonfish, and rabbit fish. The south coast has extensive fringing reefs with some of the best reef systems off Polhena and Mirissa. The most famous, Hikkaduwa has forests of branching coral in all sizes and colors. The south coast also has many sea anemones hosting several species of anemone fish that are certain to provide many hours of entertainment for divers as well as providing an unending possibility of photo opportunities for underwater photographers. In addition to what are termed true coral reefs, Sri Lanka has an extensive system of rocky reef habitats. Large boulders dominate the underwater seascape on the south coast and parts of the northeast coast around Trincomalee. These provide innumerable hiding spots for marine animals as well as interesting caves and swim-through to be explored by divers. In addition, mixed rock and sandstone reefs that are remnants of former coastlines can be found around the island. Many of these habitats are now colonized by hard and soft corals and research has indicated that fish diversity is highest on such reefs compared to all other marine Habitats in Sri Lanka.

There are also several deep coral habitats located offshore, around five to fifteen kilometers off the coast. Some of the best deep coral reefs are found along the west coast off Kalpitiya, Negombo, and Colombo. Even though these invaluable ecosystems provide more environmental benefits and economic gains to the country, they are more vulnerable to pollution and other environmental factors. Some of the coral patches around the country have already been damaged and bleached due to these negative effects. However, there are very few continuous studies done to find out the causes for these results while very few attempts have been made to restore these valuable ecosystems. On the other hand, there is a big potential for replanting corals here as a tropical country for commercial purposes also but still has not come into practice. Therefore, this pilot project is conducted to determine the feasibility of replanting for the restoration of the ecosystem

1.3 Aims and Objectives

The main purpose of this study is to use ceramic glazed tile waste as an eco-friendly, sustainable solution. Also, three objectives were achieved in the study. They are,

1. To study the marine biological and marine geological environment in the Sri Lankan coastal area.
2. To investigate the ceramic glazed tile waste production, applications, and the possibility of reusing ceramic glazed tile waste in the Sri Lankan context
3. Developed the best mix and structural arrangement to maximize the strength and cost-effectiveness of the Marine Concrete Modular.

1.4 Methodology

The literature review reveals several gaps in the current research. Specifically designed for coral regrowth, the optimal mix proportions for such concrete, and the long-term impacts on marine ecosystems. Identifying these gaps helps in formulating the research objectives and hypotheses for this research

This project investigates the use of ceramic tile waste in creating concrete modular designed to support coral regrowth, with a systematic approach that combines thorough research, experimentation, and field implementation. The process begins with an in-depth literature review, which explores existing studies on coral transplantation techniques, the role of concrete structures in marine conservation, and the potential environmental impacts of incorporating waste materials like ceramic tiles. By identifying gaps in the current body of knowledge, the review provides a foundation for further exploration. Following this, laboratory experiments are conducted to develop optimal concrete mix designs. These experiments involve using ceramic tile waste as a partial replacement for fine aggregates in various proportions (25%, 50%, 75%, and 100%), testing the material's performance in terms of strength, workability, and environmental compatibility.

To achieve the desired improvements, foam concrete was explored as a viable method. Chemical foaming was employed using a detergent as the foaming agent. Laboratory experiments were conducted to identify the optimal foam content, and the best incorporation emerging as the most effective composition. This mix achieved a balance between weight reduction, cost efficiency, and enhanced surface quality. Additionally, the increased porosity of the foam concrete provided conditions conducive to coral colonization and growth, replicating the natural environment of coral reefs. The X-ray diffraction (XRD) testing ensures that the ceramic waste does not contain harmful substances, such as heavy metals, that could negatively affect marine ecosystems. The results confirm that ceramic tile waste is primarily composed of inert materials, making it a safe option for use in marine environments.

Two modular designs, Coral Hab and Marine Condo are developed for deployment. Coral Hab structures are designed to either lie freely on the seabed or be attached to existing underwater infrastructure, offering flexibility in how they are used. However, some challenges arise in adapting these structures to the specific conditions of the marine environment. Marine Condo structures, on the other hand, are designed for greater stability, particularly in high-energy marine environments such as areas affected by tides, storms, and floods. These modular n can be secured to the ocean floor or infrastructure and serve multiple purposes, including acting as breakwaters and providing habitats for marine life. Additionally, they can be inverted to support mangrove growth, showcasing their versatility in marine conservation efforts.

The modular are deployed at Polhena beach in Sri Lanka, where coral growth and the broader environmental impact of the structures are monitored over an extended period. Data on coral growth rates, health, water quality, temperature, and biodiversity are collected to evaluate the effectiveness of the concrete structures in promoting coral regrowth. This monitoring phase provides crucial insights into how well the modular functions in a real-world marine setting. The collected data is then systematically analyzed using statistical and computational tools to assess the performance of the concrete modular in terms of strength, durability, and contribution to coral regeneration. The analysis shows that the ceramic tile waste-based concrete performs well, indicating that it is a viable material for promoting sustainable coral regrowth.

The project concludes by drawing meaningful insights from the data and identifying several areas for future research. These include long-term monitoring of the coral growth on the modular, exploring the potential use of other construction waste materials in similar applications, and scaling up the pilot project to cover larger marine areas. These recommendations are aimed at advancing both marine conservation efforts and sustainable construction practices. The structured methodology, from literature review to field deployment and data analysis, ensures the reliability of the findings and their potential to influence future research and practical applications in marine habitat restoration. Ultimately, the study contributes to sustainable waste management by repurposing ceramic tile waste in a way that benefits marine ecosystems, offering a promising solution for environmental conservation and construction waste reduction

1.5 Main findings

The study addressed the dual challenges of coral reef degradation and ceramic waste management, focusing on Sri Lanka's coastal areas. Ceramic tile factories in Sri Lanka generate substantial waste, including ceramic powder, glaze, and sludge, with no established local mechanisms for disposal. This waste, which can persist in the environment for years without decomposing, presents a severe long-term problem. While individual factories have sought solutions, a common approach is necessary to handle this waste sustainably. Given the powdery nature of tile-squaring waste, it is particularly suitable for reuse in manufacturing products like concrete. Advanced techniques for waste management exist globally, but they are underutilized in Sri Lanka. The study explored the reuse of ceramic tile waste as a partial replacement for fine aggregates in concrete. Laboratory testing, including X-ray diffraction (XRD), confirmed that the ceramic waste used in the study contained no harmful substances, ensuring environmental safety. The compressive strength of the concrete increased with the incorporation of ceramic waste up to an optimal level, with the highest strength achieved using a 1:3 mixture of ceramic tile waste to natural sand and a water-to-cement ratio of 0.5. However, workability decreased as tile waste content increased, underscoring the need for precise mix optimization.

The concrete mix was converted to foamed concrete to enhance workability, reduce segregation and bleeding, and improve hardened properties. The inclusion of air voids in the mix reduced material costs and improved porosity, which facilitates coral growth within the deployed modules. Incorporating foam concrete emerged as the most effective method, with 20% foam content identified as the optimal composition for cost efficiency, weight reduction, and improved surface quality. Using Form Concrete provides the highest cost savings compared to both conventional concrete and tile waste usage. The total cost without using waste amounts to Rs. 1.7 million, whereas incorporating tile waste reduces the cost to Rs. 1.5 million, resulting in savings of Rs. 180,959. However, by using Form Concrete, the total cost drops further to Rs. 1.2 million leading to overall savings of Rs. 375,261.75 compared to conventional concrete.

1.6 Dissertation Structure

Chapter 1	Objectives, designs, background, and Problem statement of the study are presented. This review delves into existing studies, with a particular focus on the methods employed, evaluating their respective advantages and disadvantages to inform the current research framework.
Chapter 2	Following the literature review, data collection is undertaken to gather pertinent information on concrete modular used for coral regrowth and data associated with ceramic tile waste.
Chapter 3	This section explains the process of casting concrete using glazed ceramic waste. It covers the tests performed, such as X-ray diffraction (XRD), slump test, sieve analysis, and compressive strength test. The goal is to find the best replacement for sand with ceramic waste, while using foam concrete to lower costs, reduce weight, and improve surface quality.
Chapter 4	Illustrates the creation and deployment of concrete structures, highlighting inspiration and the progress of coral reformation in the sea.
Chapter 5	Concludes the study, providing a brief overview of progress and explaining why the chosen mixes were deemed the most effective method for casting concrete.

2 LITERATURE REVIEW

2.1 Chapter Introduction

Past literature shows many aspects that can be useful for the study such as similar studies conducted in different countries, what they have used, what the limitations are regarding similar studies etc. There is a brief explanation of what corals are and why these corals are important to marine ecosystems out of all the ecosystem types around the world. Also, how these corals are linked to other lives such as humans and animals are included in the study not just around the world but also mentioning Sri Lanka. This section clearly shows why choosing ceramic glazed tile waste is the best solution to produce a concrete mix and why concrete is the best solution to reform corals rather than materials like plastic and metal.

2.2 Environment ecosystem

Today we face a larger portion of environmental problems than people have ever faced compared to history. These changes also include the distributions and exchanges of elements on a larger scale. To better comprehend the processes regulating the structure within the patterns of responses of ecosystems to stress, it is necessary to have a solid grasp of fundamental ecological principles to learn how to manage ecosystems to combat the dangers (Opportunities in Biology, 1989). Ecology plays a major role in biology as it links directly to problems and concepts that are shown in the public domain. Other areas in biology play a part in the world, but the major relevance comes from this part. Previous research demonstrates naturalism's interest in creatures and how they relate to their habitats, and this line of inquiry continues to form the basis of fundamental ecological study. The study of ecology is both exciting and challenging due to the diversity of creatures and the relationships that exist between them. There isn't a clear-cut method to distill such variety into a set of principles that anybody can grasp and follow. Instead, one must examine a wide range of varied cases and look for overarching themes that connect them all.

Almost often, it is challenging to determine the area in which experiment, or comparative survey results are applicable. Nevertheless, there are several crucial ideas. The most important of them is evolutionary theory, which explains how natural selection, random variables, and historical limitations worked to create the patterns we observe in nature. Other ideas, including succession and community, offer organizing ideas.

Many ecological issues can't always be solved by testing and instead require a comparative approach. Ecological experiments frequently can only be conducted on limited temporal and geographical scales due to aesthetic and practical considerations. However, there is potential for large-scale, lengthy trials, and they have produced significant findings. In its broadest sense, ecology heavily relies on the comparative method when attempting to organize complexity. The characterization and clarification of patterns form its scientific foundation. Many of the most intriguing and important issues in the subject are so complicated that a reductionist approach is unable to tackle them. Ecology is distinct from the majority of the rest of biology in this regard.

In ecology, there is a significant shift from explanation to prediction. In managing ecosystems and addressing environmental risks during the past few decades, we have thereby accumulated a variety of unusual experiences that do not appear to fit into any pattern. Despite these unexpected results, we are building a more reliable forecasting hypothesis. The problem facing ecology is to create more accurate criteria for categorizing events and to build a framework that can consider our prior experiences, compile our huge but sometimes ad hoc knowledge, and act as a foundation for prediction (Opportunities in Biology, 1989). Being fond of ecology or having great knowledge of ecology leads to finding information on ecosystems around the world. Learning about these ecosystems will give significant knowledge on how these ecosystems are linked and their interrelationships. The next section is focused on the types of ecosystems to provide a better idea of how each ecosystem works and how they are connected.

Types of Ecosystems

Ecosystems can be divided into two sub-categories such as terrestrial and aquatic. Terrestrial ecosystems are land based and aquatic ecosystems are water based or marine based.

- Forest Ecosystem

The area on Earth is covered with forests to a degree of around one third. Trees are the dominant vegetation in this habitat. The type of trees present, and the amount of precipitation received distinguish the various forest ecosystems. In a forest, a wide range of plants, notably trees, animals, and bacteria cohabit with the abiotic aspects of the environment. Forests are the main carbon sink and a component in controlling the earth's temperature.

- Grassland Ecosystem

Most of the vegetation in a grassland ecosystem is made up of grass and plants. Savanna grasslands, tropical grasslands, and temperate grasslands are all examples of grassland ecosystems.

- Desert Ecosystem

The main abiotic determining element of a desert environment is the amount of rainfall. Less than 25 millimeters (about 0.98 in) of rainfall annually in desert areas. The terrestrial environment of a desert is characterized by significant temperature differences between day and night. There is minimal organic matter in the soil, which is rich in minerals. Aquatic Ecosystems are surrounded by a body of water, it can be either an ocean, river, or lake. These can be divided into two type freshwater and marine ecosystems.

- Marine Ecosystem

The marine ecosystem includes the oceans and seas. They are more diverse and have higher salinity than the freshwater environment. Corals can be seen in this ecosystem section. When discussing marine ecosystems, it’s important to know about its aspects. These aspects can be either geological or biological. Next section clearly explains what the biological and geological aspects in a marine ecosystem.

Out of all the ecosystems marine ecosystems play a major role in every being’s life not just for aquatic life. Humans and other animals’ major food chains are associated with marine ecosystem. Hence, it is important to focus on marine ecosystems.

2.3 Marine Biological and Marine Geological Environment

Based on their ecological traits and the marine species that inhabit them, the benthic and pelagic worlds of the biological marine environment are separated into two main categories (Ocean, 2022). The ocean bottom, from sea level to the deepest parts of the ocean, is called the benthic realm. Benthic creatures are those that reside in or on the bottom. The littoral zone, which stretches from high tide to a depth of roughly 200 m (660 ft), and the deep-sea region are the two divisions of the benthic realm based on depth. The sessile and motile benthic life forms are both. They play a significant part in the food chain and are found everywhere from the near-shore littoral areas to the deep depths. Benthic organisms can either live by predation, sifting organic material out of the water, or scouring the bottom for organic waste that has accumulated there. Only in the euphotic zone, which is the ocean's highest 100–200 m (330–660 ft), where sunlight may enter, can benthic plants survive. The deep regions of the benthic realm are not particularly populated, except for the areas near hydrothermal vents where chemosynthesis offers an alternative food source. The whole body of ocean water that envelops the benthic realm is known as the pelagic realm. It is split horizontally into the marine province and the lush near-shore neritic province. The euphotic, or photic, zone and the aphotic (without sunshine) zone are separated vertically. The euphotic zone is populated by plankton, which drifts freely, and species with limited mobility. Most plankton are minuscule or almost microscopic.

Diatoms, dinoflagellates, and coccolithophores are examples of floating algae and photosynthetic bacteria, together known as phytoplankton. Heterotrophic plankton, often known as zooplankton, are marine creatures that float, and protozoans that depend on phytoplankton for nourishment. The two most common protozoan zooplankton that release tests that become integrated into the sediment of the ocean floor are foraminifera and Radiolaria. There is a planktonic stage that many young swimmers (like shrimp) or bottom dwellers go through. Nektonic life forms are marine creatures that can move on their own. Whales, fish, and squid are a few examples of marine nekton (Ocean, 2022). Many characteristics dignify marine ecosystems.

2.4 Characteristics of Marine Ecosystem

The world's oceans and seas that are below the mean high tide mark are considered marine habitats. The shape of the oceans near shore, offshore, and deep-water zones are related to marine ecosystems. The section discusses four characteristic types of a marine ecosystem. The characteristics are as follows, studying the characteristics of marine ecosystems is very important as the study's major task is to deploy a structure to reform corals. These structures should not be a threat to marine life or their habitats. So, it's important to know about the surroundings of marine ecosystems when developing such structures because it should be familiarized with the characteristics mentioned below.

2.4.1 The Temperature of the Marine Ecosystem

One of an ecosystem's crucial qualities is temperature. While the marine ecosystems nearest to the poles have chilly water temperatures, those towards the equator enjoy rather warm water temperatures. Things living underwater depend on the marine ecosystem's temperature for their survival (Marine Ecosystem: Characteristics and Types | Earth Reminder, 2022).

2.4.2 Water in the Marine Ecosystem

As a blue planet, Earth. Well, the water bodies that are found on the surface of the Earth deserve the most praise. About 90 percent of the water on Earth's surface, which makes up about three-quarters of its surface, is found in marine water bodies including seas and oceans. Because of the water's salinity, or saltiness, people refer to it as sea water. About 96.5 percent of marine water is clean, while the remaining 3.5 percent is made up of dissolved substances including calcium, potassium, sodium, magnesium, sulfur, and chlorine (Marine Ecosystem: Characteristics and Types | Earth Reminder, 2022).

2.4.3 Importance of sunlight

Ecology has traditionally depended heavily on sunlight. All living things rely on sunshine in one way or another to meet their demand for sustenance. Because they use sunshine to create food, plants are regarded as the major producers in the marine ecosystem. These basic producers are where the food chain begins, and it progresses successfully to the apex predators.

The essential factor in keeping the marine ecosystem's food chain in optimal balance is sunlight. More importantly, the depth of the seawater significantly impacts sunlight availability. The marine ecology has an aphotic zone where sunlight can penetrate and aid photosynthesis. On the other hand, the photosynthetic process is hampered in the aphotic zone where sunlight cannot penetrate (Marine Ecosystem: Characteristics and Types | Earth Reminder, 2022).

2.4.4 Biodiversity in the Marine Ecosystem

To ensure their existence, marine environment animals have adapted to the aquatic culture. As an illustration, fish have gills that enable them to breathe underwater. The maritime ecology supports a wide variety of plant and animal species. Among the widespread aquatic species are,

- Plants
- Fishes
- Mammals

Temperature, water, sunlight, and biodiversity are the four major characteristics that can be mentioned regarding marine ecosystems. Each of these characteristics are included in all types of marine ecosystem. Next section discusses the types of marine ecosystems.

2.5 Types of Marine Ecosystem

In Open Marine Ecosystems, the upper layer of the ocean, where sunlight may easily penetrate, is known as the marine environment. Up to 150 meters (about 492.13 ft) below the surface of the water, there is an open marine habitat. Numerous marine organisms, including plankton, algae, whales, jellyfish, and others, can find a home in the open marine ecosystem (Marine Ecosystem: Characteristics and Types | Earth Reminder, 2022).

In Deep-Sea Marine Ecosystems, deep-sea marine ecology refers to the ecosystem on the ocean floor at great depths. Various animal species may be found on the seafloor up to a depth of 1,000 meters (about 3280.84 ft) in the deep-sea marine ecosystem. One of the biggest obstacles to reaching the seabed is sunlight, yet the species has adapted to the local marine environment. Deep-sea marine habitats are home to a wide variety of animals, including squids, fish, elephant seals, sperm whales, crabs, worms, certain sharks, etc. In Saltwater Wetland Marine Ecosystems, the saltwater wetland environment refers to the coastlines of oceans and seas. Salt marshes and saltwater swamps are the two different forms of saltwater wetland marine ecosystems. In contrast to salt marshes, where grasses predominate, saltwater swamps are dominated by trees. In the saltwater wetland habitat, frogs, reptiles, a few migrating birds, shellfish, a few fish, etc. are frequently encountered water species (Marine Ecosystem: Characteristics and Types | Earth Reminder, 2022).

The marine environment of the estuary contains primarily organisms from the nearby area. This environment is crucial for fish, shrimp, and other animal species' larval stages (Marine Ecosystem: Characteristics and Types | Earth Reminder, 2022). In Mangrove Marine Ecosystems, Mangroves are a unique variety of saltwater wetland found in various tropical and subtropical coastal areas. Specialized tree species that can endure in saltwater habitat live in mangrove swamps. These mangroves are distinguished by a unique variety of roots that may take up oxygen to live. Above the water's surface, the roots are spread out. Many different species, including shrimp, jellyfish, birds, sponges, crabs, fish, crocodiles, etc., can find refuge in the mangrove habitat (Marine Ecosystem: Characteristics and Types | Earth Reminder, 2022). When explaining Sandy Beach Ecosystems**,** comparing Sandy's environment to other maritime ecosystems, it has a very low level of biodiversity. The ecosystem of the sandy beach has a very diverse habitat. The organisms present in the ecology of a sandy beach, however, have evolved to thrive in a continually shifting habitat. Sea turtles, and sea lions, are among the species that have established homes in the ecosystem of the sandy beach (Marine Ecosystem: Characteristics and Types | Earth Reminder, 2022). In Kelp Forest Marine Ecosystems**, t**he kelp forest ecology can be found in noticeably colder water. This ecosystem's typical temperature ranges from 42 to 72 degrees Fahrenheit at depths of up to 60 to 90 feet. Seabirds, shorebirds, invertebrates (such as crabs, sea stars, snails, etc.), fish, and mammals all live in the kelp forest habitat. In Polar Marine Ecosystems, the temperature of this sort of marine habitat is too cold because of how frigid the polar climate is.

Rocky marine habitats are made up of rock coastlines, rock cliffs, boulders, tidal pools, etc. Species like lichens, birds, and invertebrates (such as lobsters, urchins, barnacles, sea stars, sea squirts, and seals) are typically found in rocky maritime ecosystems. A distinctive environment that supports a wide range of plant and animal life is the marine ecosystem. In comparison to other ecosystems, all these species serve as good examples of a strong food chain. The terrible thing is that by contaminating the environment by dumping unneeded rubbish, people are ruining such a remarkable ecosystem. Our rubbish is being dumped into the seas and oceans, severely harming the marine ecosystem. Healthy coral reef ecosystems are home to both hard and soft corals, invertebrates of all sizes, and even enormous creatures like sharks and dolphins. Reefs are built by hard coral species. The foundation of a reef is the coral's limestone skeleton, which supports tiny organisms known as polyps. After the polyps die, just their skeletons are left (Marine Ecosystem: Characteristics and Types | Earth Reminder, 2022). Out of all the aquatic ecosystems, the most endangered ecosystem is Coral reef marine ecosystems. The focus should go on to preserve and protect coals as well as reform the Died or dying corals. Also, the threat for this specific ecosystem is amicable compared to other aquatic ecosystems. So, the focus of the study was moved to coral reef marine ecosystems.

2.6 Coral reef marine ecosystems

Only tropical rainforests equal coral reefs in terms of biological diversity on the planet. Coral reef marine ecosystems can vary with the locations, climate, and topographical features. So, it’s important to understand the features of coral reef ecosystems around the world and most importantly in Sri Lanka.

2.6.1 Worldwide coral reef ecosystems

Numerous species of coral live in our seas, some in shallow, warm water and others in deep, icy water. It's difficult to tell with absolute confidence since there is always the potential that there are coral species that no one hasn't yet discovered, just like with any other group of creatures. Every year, new animal species are discovered. We can only estimate the number of species that have been found, named, and described. The IUCN Red List includes them and updates them annually. The number of described species across various taxonomic categories is shown in the graph. The variations are exhibited in Figure 2.1

Some of the most exquisite and interesting living forms on the planet may be found in coral reefs. Only a small percentage of people will ever get to see one up close since, like most marine species on the earth, they reside in our waters. Nevertheless, they are significant to societies worldwide. More than 450 million people are located near coral reefs and depend on these nearby corals for their work in more than 100 different nations. Through the goods and services, they offer, they are thought to create $375 billion (about $1,200 per person in the US) annually. They are so important because they serve as the foundation for the many ecosystems that are created on top of them.

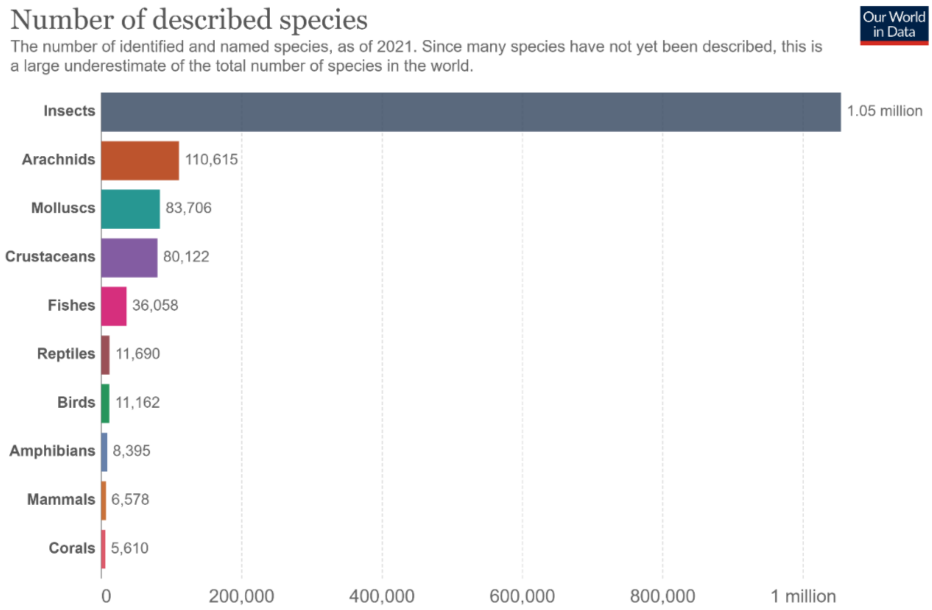


Figure 2.1: Species amounts in the world

Source :(Ritchie and Roser, 2022)

Corals make up just 0.5 percent of the ocean floor. Yet they provide habitat for over 30% of the marine fish species found worldwide. More than 500 billion corals live on reefs in the Indo-Pacific area, which includes Australia and Southeast Asia. More trees than there are in the Amazon jungle may be found there. Corals are part of the phylum of cnidarians, a class of over 11,000 aquatic creatures. The majority are marine creatures. Shallow, warm-water corals and cold, deep-water corals are the two primary categories of corals. Warm- and cold-water reefs operate extremely differently. Corals construct a tough exoskeleton from calcium carbonate found in ocean waters. But where they acquire their energy is the secret to their success. Microalgae known as zooxanthellae live in symbiotic relationships with warm-water corals. Corals get most of their energy from algae, which photosynthesize for them. 6 Without them, these corals couldn't live.

Only by residing near the surface, where there is plenty of light, can they do this (Ritchie and Roser, 2022). The majority of cold-water corals dwell 200 meters (about 656.17 ft) below the surface, where photosynthesis is impossible. These symbiotic algae are absent in cold-water corals, which obtain their energy by feeding on debris on the ocean floor. So, a reef is a collection of corals. Like a group of them. There are more than 2,000 known species of coral, which may be used to build reefs. Each can develop at a completely different rate and can create its structures. For instance, the Caribbean is home to the reef-building coral Acropora palmata. It takes the name "Elkhorn coral" from its intricate structure, which has branches that almost resemble antlers. It grows between 5 and 10 cm (about 3.94 in) a year, which is a rapid rate. Compare that to the Porites lichen species, which is widespread in lagoons and grows in very flat, smooth plate-like forms. Typically, a startlingly vivid yellow. Brain coral, which most frequently occurs in the Favia species and forms spherical shapes with grooved surfaces resembling the human brain (Ritchie and Roser, 2022).

As a result, a diverse range of animals may construct reefs, creating extremely intricate structures. All these species have benefits and drawbacks. For instance, the branching Acropora palmata is more susceptible to breaking when subjected to damage. But it immediately grows back. Brain coral is far more storm-resistant because of its compact, spherical structure, which is more difficult to destroy. The drawback is that it develops more gradually. These variations affect how corals react to mounting stressors and how reef structures may alter over time (Ritchie and Roser, 2022). Warm-water corals prefer water that is between 23 and 29 °C in temperature. Coral species frequently inhabit seas that are quite warm, which is poor news for their prospects as the oceans are warm. They can only endure a temperature increase of one or two degrees before it exceeds their tolerance limit. The tropics are home to numerous important reef clusters (Ritchie and Roser, 2022).

The most well-known is the Great Barrier Reef. It spans 2,300 kilometers (about 1429.15 mi) from the Torres Strait, south of Papua New Guinea, along the eastern coast of Australia, making it the biggest coral reef system in the world. It is the biggest construction made entirely of living things. Even from space, it is readily apparent. Some of the most diversified environments on the globe may be found there, along with many other reef systems. We must act if we wish to stop the deterioration of these ecosystems. We run the danger of permanently harming them if we don't (Ritchie and Roser, 2022).

2.6.2 Sri Lankan Coral Reef Ecosystems

In Sri Lanka, there are three different types of coral reefs: barrier, apron, and fringed. Although there are many sandstone and rock reefs in Sri Lanka, boulder reefs are typical on the country's southern and eastern coasts. True coral reefs, on the other hand, are far less common; they only cover around 2% of the coastline, predominantly along the southwestern, southern, and eastern shores, although offshore patch reefs cover a larger area. Less developed coral reefs are more common near the coastal islands of the Jaffna Peninsula. There are now 183 species and 68 genera of native corals known. There are currently just two marine sanctuaries, even though many maritime regions have been designated as needing protection. The first national marine sanctuary was formed in 1979, and the Hikkaduwa marine sanctuary, which is situated in the southern region, is one of Sri Lanka's most heavily developed tourist destinations. Its perimeter is 45 hectares, while the sanctuary's interior and bordering coral reefs total roughly 25 ha. A near-shore coral reef with roughly 60 coral species and 168 fish species is present in this region. 1992 saw the establishment of the Bar Reef as a marine sanctuary. It is situated close to the Puttalam Lagoon, west of the Kalpitiya Peninsula. The sanctuary covers 306.7 km^2 in total. True coral reefs are supported by the 70 km^2 core Zone. The Bar Reef is home to over 300 species of reef-associated fish, some of which are unique to this location (such as Chaetodon). After mentioning all about the worldwide and Sri Lankan coral reef marine systems it is important to discuss the structure of the corals and how it is formed to get a better idea on what type of structures help it to grow and more over to check whether they can be born in other environments rather than its normal habitats.

2.7 Structure of Coral Reef in Marine Ecosystem

Reforming coral is not an easy task. There are various types of corals all around the world. Each coral type requires suitable geological aspects, water levels, temperature etc. Hence a clarification of coral should be done and before that the inside of a coral should be examined to study what the corals need to grow or reform. This section helps the study to understand what kind of corals are more suitable for the selected locations and what kinds of aspects it needs to reform.

2.7.1 Structure of Corals

Figure 2.2 shows the structure of corals, the definition of corals, and their uses. In the figure, the circled part consists of the anatomy of a coral addressed below. Anatomy of the coral consists of tentacles, a mouth, a digestive sac, and a skeleton. Also, the above poster indicates that the polyps are the basic building block of the corals. It states that the skeleton is made of Calcium Carbonate. The coral's overall structure is clearly shown in Figure 2.2.

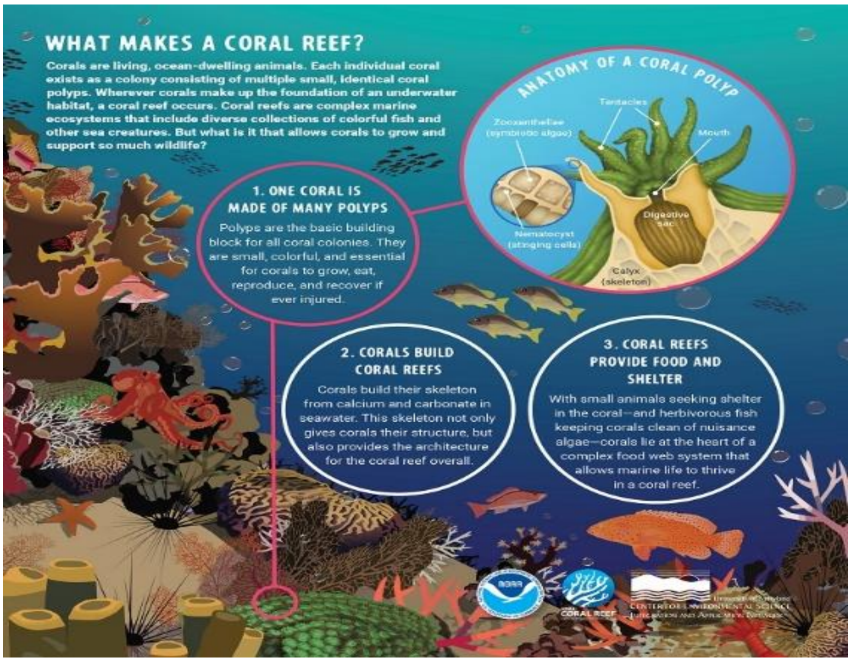


Figure 2.2: Types of coral reef formations

Source: (NOAA's Coral Reef Conservation Program (CRCP) - What Makes a Coral Reef, 2022)

Two layers of cells make up the body, which is divided by a jelly-like layer devoid of internal organs. Nematocysts, specialized stinging cells that corals have on their retractable tentacles for catching prey, are utilized to sting prey. The polyp secretes calcium carbonate, which hardens into the coral's skeleton. A corallite is a cup-shaped skeleton that a single polyp deposits. Polyps feed on the sugars generated by the photosynthesizing zooxanthellae, a form of algae, and collect food particles with the nematocysts (stinging, poisonous cells) in their tentacles. These algae are shielded by coral tissue from herbivorous grazers, and in return, the algae consume many of the waste products produced by the polyps, such as carbon dioxide, nitrogen, and phosphorus. Figure 2.3 shows how soft corals are dependent on the zooxanthellae, which are microscopic algae that dwell inside them.

Figure 2.3: Soft Coral

Source: Nick Hobgood

2.7.2 Creation of coral reefs

Coral polyps secrete layers of calcium carbonate beneath their bodies, which are then used to construct coral reefs. Hard corals or "reef-building corals" are the species of coral that construct reefs. Sea fans and sea whips are examples of soft corals that do not form reefs. If the local dangers to coral reefs are kept to a minimum, the calcium carbonate that hard corals produce offers a foundation for young corals to settle upon, and the corals will gradually accumulate and produce a healthy, bright coral reef. They also act as the starting point for future corals when these creatures perish.

2.7.3 Growth of Coral Reef

Under their bodies, hard corals frequently release calcium carbonate. This develops into a solid, rock-like structure that may be colonized by other coral larvae. The size of a coral reef increases over time as calcium carbonate amasses and corals procreate. Other creatures and species are drawn to the diversified habitat as a coral reef expands and finds areas to settle and call home. Coral reefs are home to more than 25% of all marine species. Each one contributes differently to the overall health and integrity of the ecosystem.

2.7.4 Reproduction of corals

Many hard corals have broadcast spawners, which means they release a significant amount of sperm and eggs into the water. Synchronized coral spawning, an occasion that normally takes place on a specific day and at a specific time, is what causes this. In the sea, sperm and eggs combine to create coral larvae. The larvae are first drawn to the light, which causes them to swim to the surface where they can be carried away by the currents of the ocean. Before they find a reef to settle on, they may roam for days or even weeks. The larvae seek hard, rock-like structures to attach themselves to, and studies have revealed that they choose healthy reefs with good environmental circumstances. After settling, the larvae develop into polyps to create coral colonies that keep expanding. Corals can only procreate in a healthy environment. Stressors such as poor water quality, a marine heat wave, or overfishing will cause them to focus more of their energy on surviving than reproducing.

2.7.5 Types of Coral Reef Formations

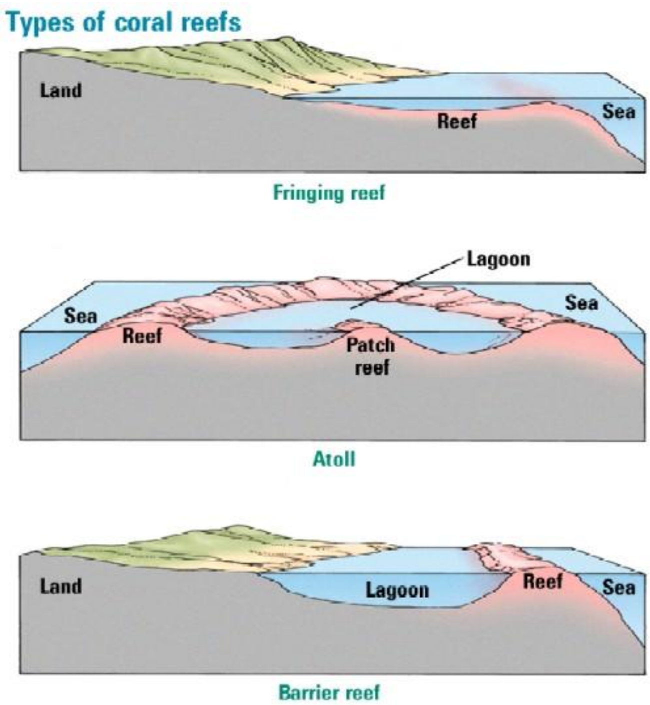


Figure 2.4: Types of coral reefs

Source: (What are coral reefs? 2022)

Fringing reefs infrequently develop near the shorelines of continents and islands. These fringing reefs may be separated from the beach by small, shallow lagoons. One reef type is the most common: a fringed reef runs parallel to the shore, as do barrier reefs; however, they have deeper, larger lagoons. B certain points on the pillar. As a result, they can act as a "barrier to navigation," and the surface may contact the water. Such as when atolls a coral ring is formed in a safe lagoon, which usually occurs in the middle of the ocean (Figure 2.4). Reefs often result when a bordering reef island collapses into the ocean. Tabular reefs form due to increases in their adjacent sea level. Patch reefs still exist, the free reefs that emerge from the continental shelf or island platform's open underside. They generally exist between the reef zone and the open ocean.

2.8 Threats to Coral Reef

Threats to coral reefs can be different around the world. Coral reefs can be damaged by natural disasters. All these natural disasters vary from continent to continent. Different fishing methods can harm the corals, and these methods are different from country to country. This section will show the different types of threats around the world and in Sri Lanka.

2.8.1 Worldwide threats

Bleaching is frequently the first danger that comes to mind when people consider hazards to coral reefs. When they are subjected to extremely heated temperatures, this occurs (Ritchie and Roser, 2022). But corals are subject to a variety of stressors. While many of them are also human-driven and have intensified in recent decades, many have naturally occurred throughout history. Highlighted the primary stresses corals are now under in the table. Our emissions of greenhouse gases come first. As a result, corals may experience three major issues: bleaching due to rising surface waters, as described; an increased danger of storm damage if storms become more frequent and stronger; and ocean acidification due to carbon dioxide emissions (CO_2). Increased CO_2 dissolved in our oceans causes them to become more acidic, which can cause calcium carbonate, which corals require to construct their skeletons, to dissolve. (Ritchie and Roser, 2022)

Our shipping and fishing operations come in second. A diverse ecosystem of marine life includes coral reefs; overfishing results in the extinction of important species required to sustain these ecosystems. Explosive fishing, dredging, boat anchoring, and shipping routes are just a few destructive activities that can seriously harm coral reefs' physical makeup. Disease and pollution come in third. The chemistry of coastal waters can be significantly impacted by human activity in coastal locations. Coastal populations may have sewage disposal systems, surrounding farms may discharge fertilizer and manure into the ocean, and shoreline developments may contribute to sedimentation and murky coastal waters. This adds an excessive amount of nutrients as well as perhaps heavy metals and pollutants to the water.

These nutrients are ideal for algae growth, and they can completely dominate the environment. They obstruct the sun and deplete the water's oxygen supply. Corals and the ecosystems they have created can disappear suddenly. These serious dangers have the potential to completely alter coral reef systems around the planet. However, grouping them into three crucial areas can also concentrate on three fundamental fixes. These are, indeed, straightforward in theory but challenging. Reduce emissions of greenhouse gases first. Second, set aside marine protected zones around coral reefs to restrict shipping and fishing. Third, control coastal development in and near important reef zones (Ritchie and Roser, 2022). Warming seas, ocean acidification, alterations in ocean chemistry, and ecosystem dynamics are not new dangers to the world's coral reefs. Throughout Earth's history, stresses on corals have varied in intensity. Some of these changes in the distant past were drastic. The so-called "Big Five" major extinctions have occurred five times in the history of our planet. Each of them involves significant alterations to both the world climate and the ocean's connectivity. 10 The world's corals suffered greatly because of these catastrophes. For many million years following each one, there were no longer any live reefs, leaving what is known as "reef gaps" in the geological record where there are no signs of any previously existing reefs.

That is, of course, assuming the worst-case scenario of extinction events. Corals would nonetheless face some stressors even in the current world devoid of people. They would be affected by cyclones and storms. Events of bleaching might occur, especially in warm El Nino years. And the dynamics of their ecosystems would undergo periodic alterations. When corals are subjected to stress, they often recover over the next years or decades. Recently, these occurrences now happen more frequently because of human demands. Instead of just occurring during warm El-Nino years, bleaching episodes occur every year, even during the 'cold' La Nia period. This implies that they have very little time to recover before another large-scale bleaching event strikes. They may experience cyclones more frequently or with greater severity.

These strains are only made worse by the pressures of overfishing, algae blooms, and the degradation of the ecosystems that corals depend on for survival. From location to region, these increasing pressures range greatly in timing and intensity. While the effects of coral bleaching have only truly increased since the 1990s, other stressors have been for longer. Populations were growing more urbanized along the seaside by the 1950s. These inhabitants brought agriculture and rising fertilizer use. This fertilizer may discharge into coastal waterways if it is used excessively or improperly, which might lead to algal blooms and significant changes in the marine ecosystem's composition. This loss goes beyond a change in species from Acropora corals. According to a study that was published in Science Figure 2.5, the Caribbean's entire coral cover decreased from 50% in 1977 to barely 10% in 2001.

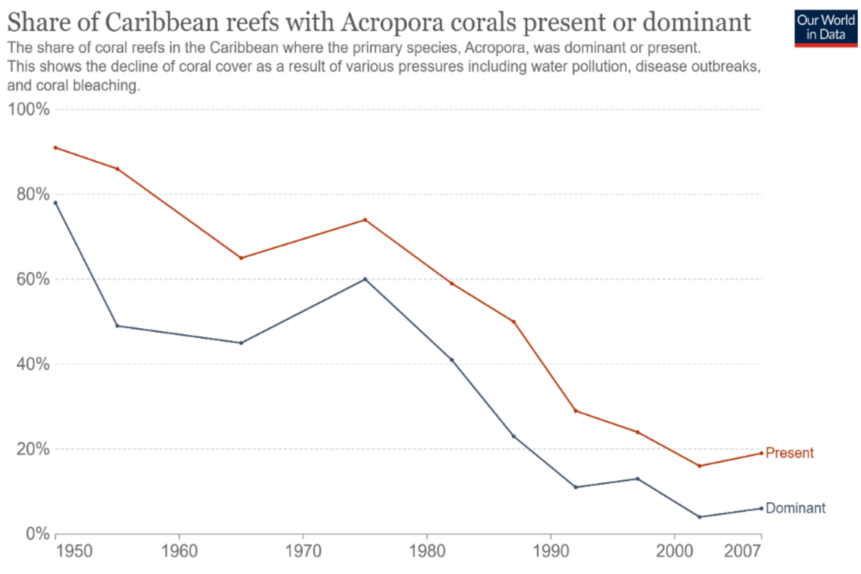


Figure 2.5: Share of Caribbean reefs with Acropora corals

Source: (Ritchie and Roser, 2022)

2.8.2 Threats in Sri Lanka

Sri Lanka's Coral Reefs are threatened by human and natural activities. Respectively overfishing, dynamite fishing, and pollution (including lastly black smog effluent plume of rare earth elements) followed by sedimentation auto load from agriculture fields and coastal development have all played a role in this upon the ecosystem. This photo provided by WWF shows the aftermath of mass coral death in 39 locations on multiple reefs off Sri Lanka's coast following two climate-induced bleaching events.

- Unsustainable exploitation of marine resources

Reefs made of coral are physically destroyed by destructive fishing methods like bottom trawling and blast fishing. By destroying the zooxanthellae, fishing techniques that employ poisons like cyanide can bleach coral reefs. Coral reefs are also in danger from overfishing fish that graze on algae. This is because grazing fish maintain certain kinds of coral-growing algae that have the potential to suffocate coral reefs. Unsustainable fishing is dangerous to 55 percent of the world's coral reefs, with most of these reefs in Southeast Asia. These activities have an impact on over 65 percent of the corals in the Indian Ocean.

- Coral bleaching

Coral reefs require a narrow temperature range to survive. Corals become stressed at higher temperatures, which disrupts their mutualistic connection with the algae that live on them. The corals suffer, as a result, losing part or all of their zooxanthellae and, therefore, their nutrients and color. The corals then look bleached, which increases the risk of coral death. Due to abnormally high temperatures, there have recently been two global bleaching episodes.The data presented in Figure 2.6 are integrated into the analysis In the Indian Ocean, coral bleaching in 1998 and destructive human activities caused more damage to coral reefs than the Tsunami of 2004(Coral Reefs – IUCN, 2022). The 1998 coral bleaching event, caused by an El Nino event, was classified as a 1 in 1000 bleaching event and damaged corals worldwide. The proportion of living coral dramatically decreased during the coral bleaching outbreak in 1998. Global coral reefs shrank by 16%, with losses in the Indian Ocean reaching 50%. 2016 saw a worldwide bleaching event following yet another warming event. The effects of the

1998 coral bleaching event on the reefs of Sri Lanka's Bar Reef and Hikkaduwa marine parks are seen in the chart below. Following the bleaching incident, the proportion of coral reefs in both the Bar Reef and Hikkaduwa fell to fewer than 10% from an estimated 80 and 60 percent, respectively.

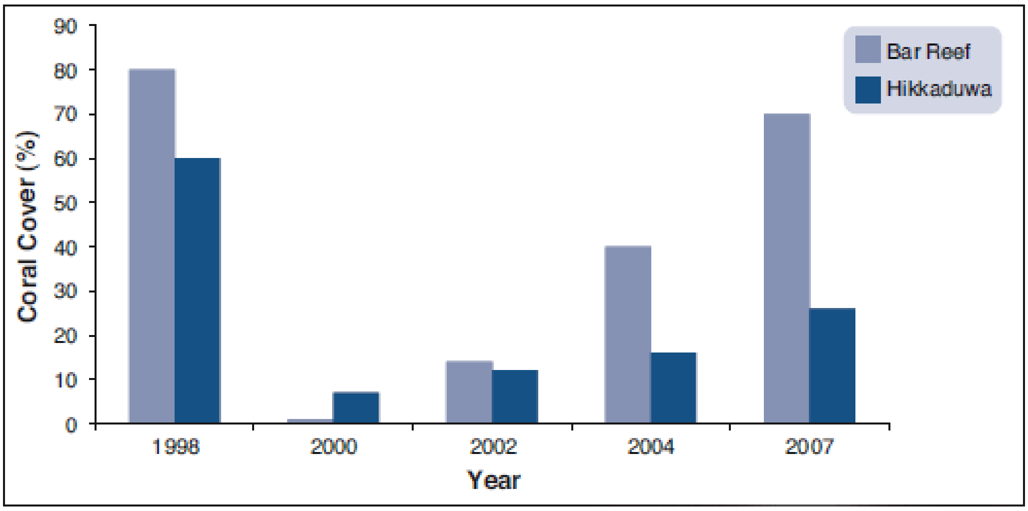


Figure 2.6: Coral covering percentage in Sri Lanka from 1996 – 2007

Source: (Data obtained from Arjan Rajasuriya/NARA, CORDIO, and GCRMN, extracted from Wilkinson (2008) Status of Coral Reefs of the World 2008)

- Ocean acidification

  Dissolved carbon dioxide produces carbonic acid, which weakens corals' capacity to construct reefs. Fewer carbonate ions are available to make calcium carbonate, which corals need to form reefs, while more carbon dioxide becomes carbon acid (Coral Reefs – IUCN, 2022).

- Coastal Development

  Coral reefs are harmed by exploration, land reclamation, deforestation, and erosion. Along with deforestation and other land management techniques, dredging and land reclamation can destroy the coral reefs' ecosystems and increase water sedimentation. The sea becomes murkier due to sedimentation, which may suffocate coral reefs since their polyps won't receive enough sunlight and may eventually perish. Additionally, nitrogen levels in the water rise due to runoff from agricultural fields, which may encourage coral development and suffocate reefs with algae (Coral Reefs – IUCN, 2022). The data is presented graphically in Figure 2.7 and Table 2.1

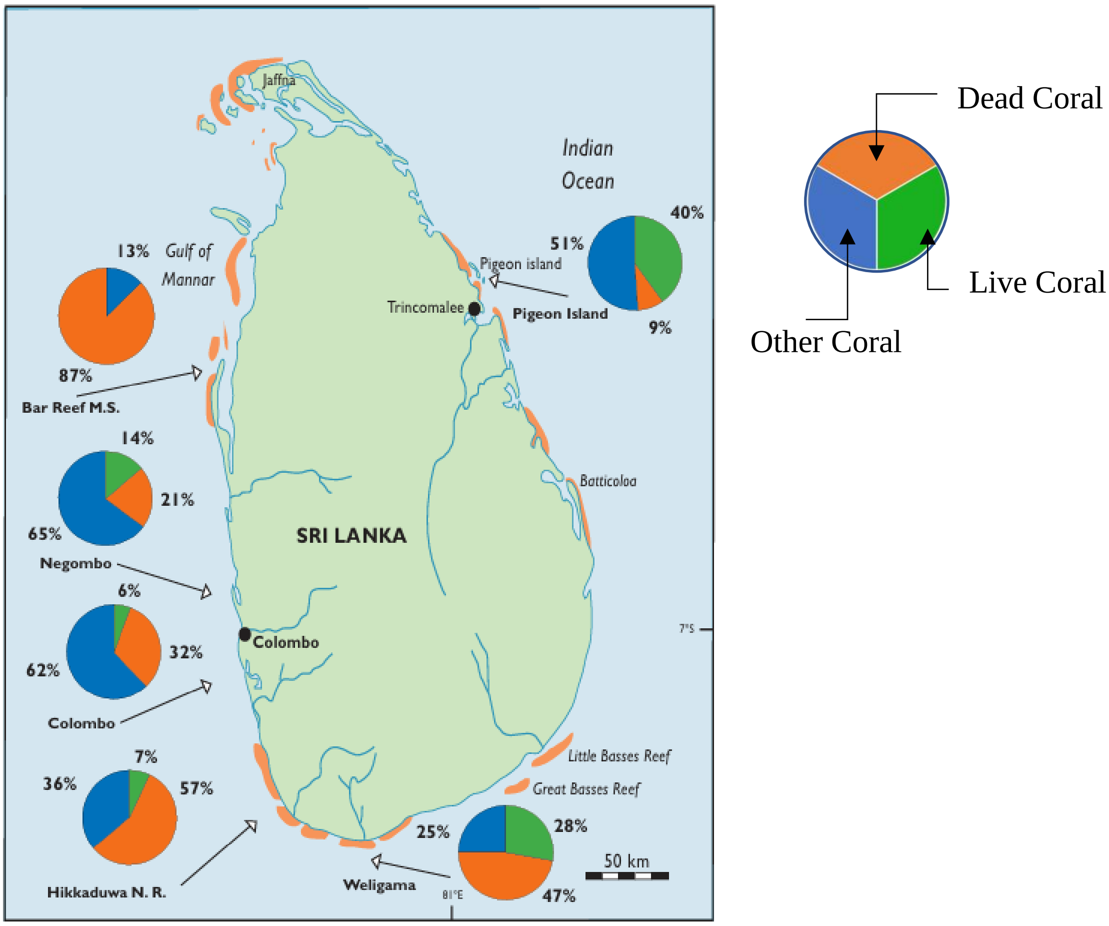


Figure 2.7: Distribution of coral reefs and post-bleaching status of selected coral habitats in Sri Lanka.

Source: Coral Reef Research Programmed, NARA 2005

Table 2.1: Percentage cover of substrate recorded from surveys conducted during 1999 at selected coral reef habitats in Sri Lanka.

Location	Depth	Live	Dead	Other
Bar Reef	0 -8 m	0	87.5	12.5
Colombo+	15 – 22 m	6.0	32.0	62.0
Hikkaduwa	0 – 4 m	7.0	57.0	36.0
Negombo+	15 - 22m	14.4	21.0	64.6
Weligama	0 – 4 m	28.0	47.0	25.0
Pigeon Island	0 – 5 m	40.0	9.0	51.0

2.9 Artificial Coral reformation

Many methods have been used to design artificial reefs that help restore the marine flora and fauna suffering from destruction. Types that resemble human-made objects (abandoned subway cars, wrecked ships) are the most common and popular. Wikipedia types of the benefit of such structures is that there would be no need to construct them. But they prohibit any microstructural development, so only algae and that sort of oyster-life can grow (though no abundant marine life). A more pinpointed solution has been the creation of reef balls. But with them being driller structures, they have no clear identity and generally do not have smaller pocket spaces that corals could just take and grow well. Also, the cement used for their manufacture is alkaline. Hong Kong, with its urbanized reef, has some of the most polluted waters in the world, and special attention needs to be allocated to avoid any further pollution. Besides, the subtropical climate provokes a vast amount of underwater sedimentation, which can be detrimental to corals. An assessment of artificial reef performance indicates that only 50% meet their objectives, the remainder having no, little, or limited success (Baine M. 2001).

Hence the solution for an artificial coral reef structure must be specific to local conditions to increase the chance of survival for the species. In the past decade, 3d printing has become a fabrication methodology in many different professions. The additive manufacturing technique is versatile and can utilize a wide range of materials, such as plastic, resin, bioplastic, concrete, ceramic, and even water-based polymers. It allows a broad range of formal divagations, which can be manipulated to optimize structure, functionality, or amount of material used. 3D printing machinery ranges from traditional printers to robotic arms and continuous feed extruders. The method permits mass customization (Sabin, J. et al. 2017) or discrete elements with specific needs (Jimenez Garcia, M. et al. 2017).

Recently, the Australian design firm Reef Design Lab has developed the 3D Printed Reefs project for the WWF Netherlands Oyster Reef Restauration project in the North Sea. The project consists of 50 units ranging in size from 50cm (about 1.64 ft) high to 120cm in height using D-shape binder jetting technology. A method that binds sand with a binder based on seawater and magnesium (Goad, A., Lennon, D. 2017). In France XtreeE and Seaboost (Egis Group), have developed a concrete, artificial 3D-printed reef, immersed in the Calanques National Park. The biomimetic yet porous reef is designed to mimic coralligenous habitats in the Mediterranean Sea.

It is composed of a structurally complex and dense biogenic substrate, which hosts many species, such as fish, crustaceans, coral, algae, mollusks, and many others (Mallet, A., Guillen, A. 2016). However, a common denominator can be considered the use of natural materials, which do not alter underwater flora and fauna and damage it further. These were the first artificial structures that needed to be suitable as microhabitats for the coral fragment of the selected coral species, Acropora, Platygyra, and Pavona corals. Secondly, the structure could provide pocket spaces in which corals could grow in a limited size horizontally, develop exponentially in the vertical direction, and thirdly prevent sedimentation, a typical subtropical underwater condition. Furthermore, the 3D-printed structures had to be based on ceramic material. Clay is like the calcium carbonate found in real coral reefs. In preparation for a worst-case scenario, in which the corals would not be able to grow and die, the structures would not pollute the underwater environment.

To come up with a solution for the objectives stated above, the research team developed a specific method that combined an algorithmic design approach for the different geometries of the design with a digital additive manufacturing process utilizing 3D robotic clay printing. The method allows for the fabrication of complex and massive pieces while optimizing production time (Rael, R. et al. 2017). The overall fabrication strategy for the complex and large pieces sought to ensure structural longevity, optimize production time, and tackle the involved double-sided printing method the overall project consists of 32 units organized in assemblies of 4 tiles each. Each of the 128 tiles has a size of 0.36 sqm. The tiles will eventually be deployed on the seabed at three different sites in Hong Kong waters (LANGE, RATOI, and LIM CO, 2019).

To allow for a manageable underwater assembly through scuba divers, tiles were designed based on a hexagonal assembly strategy with three legs each, making it easier to align the system underwater. Furthermore, the design needed to be symmetrical or based on similar patterns, because of the use of an ARMS (Autonomous Reef Monitoring Structures), which is a standardized global measuring tool for underwater life behavior. An overly irregular structure could lead to an increasingly difficult means of measuring since it would have to account for formal diversity. For the same reason, each assembly of tiles needed to be identical. As printing solid clay tiles at this scale turned out to be a challenge since they burst easily during the firing process in the kiln, the team needed to develop a printing strategy that ensured structural integrity, but also avoided any collapse of the tile during firing. Thus, the tiles are organized into three parts. The bottom layer is a porous gridded part, which acts as a structural platform and follows generic grid 3D printing concepts.

The top layer is based on a bio-mimetic approach and serves as the primary surface to attach the coral fragments. The third part is the footing which is based on three legs. They are printed on the backside of the tile after flipping. They ensure a necessary distance to the seabed for better water circulation and sedimentation prevention (LANGE, RATOI, and LIM CO, 2019). The team used a generative algorithmic design approach for the project.

Using Rhino in conjunction with Grasshopper, the focus of this design method was on developing a flexible system that enables an iterative design process, tests different design variants, and generates local specificity within the tile. Custom-made definitions utilizing other plug-ins such as Kangaroo (for form relaxation), Anemone (for periodic and loop generation), Pufferfish (for grid distortion), and Lunchbox (for grid generation) were used to create the bio-mimetic layers.-

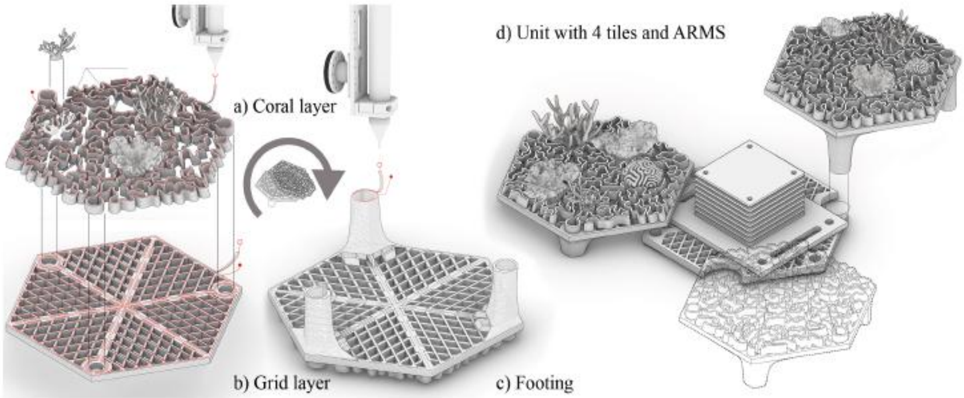
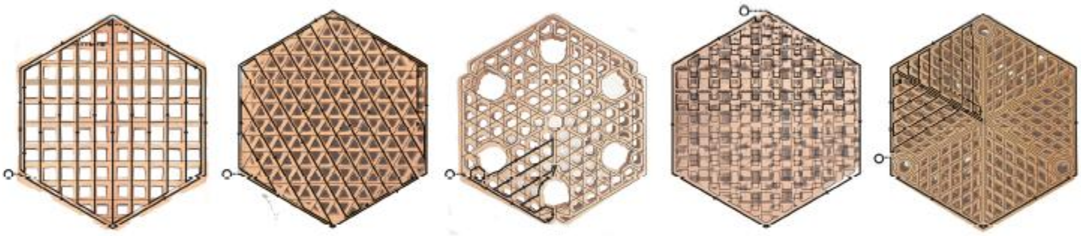


Figure 2.8: Manufacturing and assembly diagram of the study

Source: (LANGE, RATOI, and LIM CO, 2019)

Each of the three composing Part of the tile was computed into a single, continuous line, to optimize printing time. A series of different lines would require more printing time, either because they would require seam calibration (position in which the robot begins a line and commences the other), or the use of an on / off function of the extruder (extrusion stops while traveling from the end of one line to the beginning of the other). For the code generation of the ABB robot, the research team used the HAL-Plug-in for Grasshopper. This setup enabled the efficient and accurate transformation of the line geometry into the individual target planes. The first set of layers of the tile was based on a traditional grid strategy common to 3D printing. The grid was implemented to prevent sedimentation on the tile's surfaces. Figure 2.8 provides a visual summary of the Manufacturing and assembly diagram

The various types of grids were designed so that a 20 mm (about 0.79 in) diameter circle may fit within the grid's hollow openings to prevent mollusks from developing on the tile and causing potential shattering in the tile base once deployed in the ocean. The tile's size was kept at a constant 650 mm (about 2.13 ft) across the hexagon's diameter. Given the tile's large span, crack formation posed a challenge during the air-drying process of all grid types (LANGE, RATOI, and LIM CO, 2019).



GRID	A	B	C	D	E
TIME (minutes)	40-50	60-70	70-80	70-80	50-55
LENGTH (m)	152	181	228	200	170
MATERIAL USAGE (kg, clay density: 3.7 g/cubic cm)	15.1848	18.0819	22.7772	19.98	16.983

Figure 2.9: Various grid tests with overlaying printing path

Source: (LANGE, RATOI, and LIM CO, 2019)

This grid was generated with intersecting, perpendicular paths, and contained within a hexagonal boundary Refer to Figure 2.9, which shows of all the grid types, the square grid used the least material and printed the fastest. It had a total print length of 152 meters divided across 8 layers. However, the grid geometry was eventually dismissed since it did not work well with the coral layer above. Figures represent the triangular grid and, respectively, the tri-hexagonal grid. Like the square type, these grids were generated with an intersecting path strategy, angled at 30 degrees. The triangular grid had a total print length of 181 meters, while the tri-hexagonal grid had a print length of 228 meters. During the drying process, the former tended to crack and separate at the intersections, while the latter displayed typical s-cracks. Figure 2.9 represents a manipulated Peano space-filling curve cropped to the hexagonal tile.

This space-filling curve was altered such that every other member touched or intersected helped break the various stresses that occurred during the drying process. The print length of the grid was 200 m (about 656.17 ft). However, since this grid had many sharp turns within the printing path, the printing speed had to be reduced from 70 mm/s to 55 mm/s to ensure that the printed clay adhered to the layer below. Hence, making this strategy less efficient than the other grids described Figure 2.10 represents a diagrid with a bracing prototype.

The diagrid presents a manipulation of the square grid's geometry as such that its members are parallel to the bracings placed within the tile. The theory behind this strategy was that it would strengthen its structural stability against torsion and create an infill that is symmetrical around its center, which allowed the tiles to dry symmetrically. The total print length of this prototype is 170 meters. The strategy worked best with the geometry developed for the coral mimicry layer and was also the most stable solution for the prevention of cracking (LANGE, RATOI, and LIM CO, 2019).

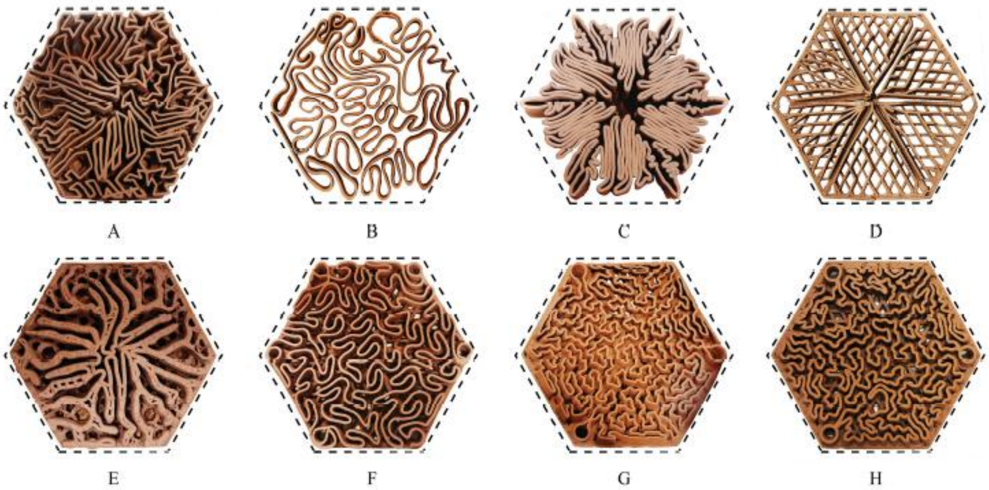


Figure 2.10: Prototypes of tested coral mimicry strategies

Source: (LANGE, RATOI, and LIM CO, 2019)

Out of the three species of corals that will eventually be inserted into the artificial reef structure, the Platygyra coral was chosen as a point of departure for the biomimetic form-finding technique. The pattern with its undulating behavior proved to hold the most potential to achieve the ridges that act as anchors for the corals, and the trenches that direct sedimentation. A series of different algorithmic strategies were tested, both in the digital and physical environment, to calibrate the relationship between generative coding, robotic fabrication, material behavior, and ergonomic factors aiding coral growth. The curve fills the space within the perimeter of the pre-determined hexagon.

It proved potential in terms of accounting for the necessary minimum distances between ridges and trenches, and it created a dynamic structure. However, the irregularity of the structure does not perform well with the clay material, leading to breakage. Figure 2.11 a prototype based on a curve derived as an outline of a circle packing logic (LANGE, RATOI, and LIM CO, 2019). Geometrically, circle packing constitutes the display of circles of various sizes on any surface, ensuring that no circles overlap, but they all touch their neighboring circles (Stephenson, K. 2003). Similarly, to the previous test, it had the potential to calibrate distances between print lines according to any given logic but did not perform well as a 3D printed clay prototype. Figure 2.11 embodies a particle growth curve, generated in a neuron growth logic, which implies that an original nucleus spreads into branches, developing in a fractal manner.

While the distances can be augmented (in the present image, the openings are too narrow), the overall shape lacks structural stability. Figure 2.11 exemplifies a logic based on the shortest path. The shortest path is a mathematical concept in which, in a network of curves, the shortest route from a line start point to line endpoints in a network is calculated. Following the diagrid planimetry, the code established a branching methodology according to the shortest path. However, the uninterrupted long lines, which didn’t branch, intersect, or deviate from the straight path, are not optimum for 3D printing with paste-based materials and do not present structural strength. Figure 2.11 represents a merger between the space-filling curve methodology and the shortest path logic. It proved to be structurally stable, but in vertical development, the print started to become inaccurate with a lot of unnecessary material deposition. Figure 2.11 represents prototypes based on a Gosper Fractal curve, which is another type of space-filling curve, mimicking the fractal development of a snowflake.

A generative growth algorithm was applied to the curve (Runion, A. et al. 2005), which then was projected on the underlying diagrid. This strategy allowed the fractal curve to deviate the straight lines only along the diagonal of the diagrid cells, which aided printing. Each fractal subdivision coincides with either the corner of a cell, a diagonal of it, or a middle point of a parametric curve of the cell. The curve was then relaxed to avoid sharp edges, which can damage coral growth. As the layers are deposited vertically, they start to taper. The curve follows the same logic within its whole geometry, with the exhibition of larger openings in the footing areas, which allows the addition of footing elements. It further was augmented to respect the size limitations of coral growth. The points were then culled and distanced from an emitter (the center of the pocket), which created additional folds in the curve. This concept also turned out to be the least cracking one and was chosen as the final strategy (LANGE, RATOI, and LIM CO, 2019). The clay tiles were printed with a DIW printing technique (direct ink writing) (Carlos, R. et al 2017), in which the layers are printed one on top of the other. This technique requires no use of scaffolding or molds, which eliminates material waste. As a printing set-up, the team utilized a standard ABB 6700 industrial robot with a delta bots linear ram extruder equipped with a 6mm nozzle. The tiles were printed directly onto the kiln shelf made of cordierite, which proved to be an excellent material for water absorption. The specific clay used was Red Terracotta Clay (P1331, Pottery crafts ltd) mixed with less than 1 % Fine Fraction Crystalline Silica. The printing layer height was set at 2.7 mm to optimize adherence. Extruding speed varied for different parts of the tiles, differing from 10.5 mm/s to 17 mm/s. Layer width fluctuated between 6mm to 11 mm, depending on extrusion speed. The grid layers were designed with a doubled printing path, to ensure enough mass to prevent cracking, which can happen due to the tension formed within the geometry during the drying process. The infill is only 65% solid, to ease the overall structure and reduce printing time. The grid layers' width was 11 mm, a thicker structure providing more stability (LANGE, RATOI, and LIM CO, 2019).

The coral-mimicry layers had a width of roughly 6mm since structural stability was established in the grid layers. The geometry was designed in a tapered manner at a 22-degree angle, so that not only did the overall ridges prevent sediment deposition, but the overall shape directs outward. The tapering was optimized according to clay behavior. The tiles were dried in a stable environment for two days before they were flipped for a second printing process that entailed the printing of the legs. The surface was manually roughened up to ensure proper adhesion between the footing and the grid layer. The tiles were then stored vertically and rotated periodically to prevent cracking and to avoid water deposition towards the bottom layers. In some prototypes, the layers were dried with a heat gun as printed, but the strategy proved no benefits as opposed to regular drying strategies. After the tiles had become bone dry during several days of drying, they were fired in a kiln at 1125C. The overall shrinkage after drying and firing was eventually 11%, which is relatively high and could be avoided by using other types of clay with a lesser shrinkage factor (LANGE, RATOI, and LIM CO, 2019). The outcome of the project was successful regarding the design process, algorithmic design strategy, and robotic 3D printing process. However, the most challenging part of the 3D printing paradigm within the "Reformative Coral Habitats" project was the drying process. Within that process, the relationship between the horizontal and vertical dimensions of the tiles seems to play an important role. While significant in the horizontal direction, with a diameter of 650mm, the height of 80mm seems not sufficient to counterbalance the tension within the tile during the drying process. While the team achieved fruitful results, it is not entirely clear how the different parameters involved influenced the process. Both the grid, acting as a base plate, as well as the biomimicry layers, have been subject to a continuous trial-and-error process of optimization. As the team was confronted during this process with much cracking, the design of the printing path and the drying process required calibration that resulted even in the design of devices that enabled the tiles to be dried vertically (LANGE, RATOI, and LIM CO, 2019).

Figure 2.11: Assembled Prototype

Source: (LANGE, RATOI, and LIM CO, 2019)

However, this is an ongoing stage. The prototypes will be deployed in underwater conditions for two years, which is estimated to be the amount of time needed for corals to start being able to form self-supporting structures (LANGE, RATOI, and LIM CO, 2019).

- Alex Goad's MARS project

Ceramic Modular Artificial Reef Structure (MARS) is an artificial structure designed and fabricated by Goad and contributed to rebuilding the coral reefs faster. The project of artificial structure for the growth of corals has been started during industrial design studies at Monash University in Melbourne, Australia which is developed at Reef Design Lab (where Goad is a cofounder with marine biologist David Lennon) at the present. This research was conducted using ceramic material to proper surface area and texture for the marine organisms to reform and find a habitat to provide safe substrate material for the growth of corals. A modular design that can be deployed from small boats that implemented by divers solved the issues had with the Goad's artificial structure used for the growth of corals. Therefore, the need for heavy-duty machinery directly reduces the costs of building the ceramic structure. Individual configurations can be easily tailored for specific projects and unique locations by snapping units together like Legos due to the system being modular. The team has tested their structure for several marine habitats. MARS systems are colonized by shellfish, small fish, and shrimp just after three months from establishment underwater according to Goad's website.

- Coral reformation in Tamarindo Reef in Culebra, Puerto Richo

About 30 kilometers east of the Puerto Rican mainland, on the island of Culebra, Tamarindo Reef was the site of this investigation. Numerous restoration efforts have been made on this reef with the primary goal of boosting cervicornis population density. Tamarindo Reef was a good candidate for our comparison research since the restoration efforts were conducted by the Puerto Rican conservation group. Sociedad Ambiente Marino (SAM), was effective in boosting the number of *A. cervicornis* and related reef species (such as juvenile fish). Synthetic corals or 3D-printed artificial corals were made using six natural colonies. To get the values, six natural colonies were carefully separated from the nail and kept safe until restoration. The restoration is done in flat reef areas. A hoop which is made from plastic is placed near the corals and base, mid and top photos will be taken every ten degrees with a camera that gives 108 photographs. Using this method, we were able to capture all the corals' morphological information, such as branch spacing and branch orientation. The real corals were placed back in their original location after the photographs were shot. The AgiSoft Photoscan application was loaded with coral-specific photos. Each coral colony's morphology was digitally recreated by software, which also produced a 3D picture. The six artificial corals were positioned on the reef in January 2017 at 0.5 meters from the real corals that served as their models.

Based on the typical distance at which coral colonies are often planted out to the reef by SAM, the distance between the natural and artificial coral was determined. Nails and plastic cable ties were used to attach the fake corals to the reef substrate. The examination was conducted between 3 and 4 meters beneath the surface.

Without the presence of people, an underwater video census was used to determine the number of fishes linked with each variety of coral. Both the fake and natural corals were captured using GoPro cameras mounted to a metal bar. After deployment, the cameras could monitor fish movement around colonies for 10 minutes without being interfered with (Tessier et al. 2005). Recorded the number of fish per minute that sought cover in the coral branches (Pagán and Mercado-Molina, 2018). The fake units were taken from the reef after the trial. Analytical statistics to ascertain if the kind (artificial vs. natural) or complexity (high vs. low) of the coral was connected to the number of fishes associated with it, a generalized linear mixed model was utilized. Results of a generalized mixed linear model were used to examine whether coral complexity (high vs. low) and type (artificial vs. natural) influence the number of fishes drawn to a coral in the Tamarindo reef.

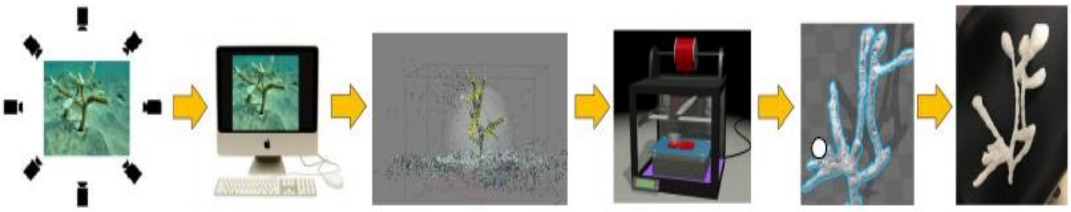


Figure 2.12: Steps followed to create artificial corals with 3D printers

Source: (Pagán and Mercado-Molina, 2018)

There were the same numbers of fish around both natural and artificial reefs. In artificial corals, the mean number of fish per colony per minute ranged from 1.12 (0.36 S.E.) to 4.55 (1.63 S.E.) and between 1.5 (0.58 S.E.) and 4.00 (0.89 S.E.) in natural colonies. Fish, on the other hand, was noticeably more plentiful among corals with great structural complexity. In general, the most sophisticated corals had three or four times more fish than the simplest corals, whether they were natural or manufactured

(Pagán and Mercado-Molina, 2018). The same fish species was discovered to be drawn to both artificial and natural coral. The most prevalent species were parrotfish Sparisoma spp., yellowtail snapper Ocyurus chrysurus, and blue-headed wrasse Thalassoma bifasciatum (both juveniles and adults). The effectiveness of artificial corals, as opposed to artificial reefs, has seldom been the subject of research, despite several studies evaluating the significance of artificial structures in luring coral reef species to deteriorated reef regions. The experiment tested the potential of 3D-printed fake reefs to draw reef fish as shown in Figure 2.12. Fish were drawn to both natural and artificial corals at comparable rates, it was discovered. These structures, however, are either costly, labor-intensive to deploy, or logistically challenging. As a result, community-based environmental groups, who are often the major funders of programs for reef restoration and protection, have not utilized them frequently (Hernández-Delgado et al. 2014).

Artificial corals made using three-dimensional printing are an alternate tool that is lightweight, portable, and reasonably priced—in instance, about US$ 45 per coral. However, producing 3D-printed corals requires less time, labor, and materials than growing corals in nursery units. As a result, programs for restoration and conservation might use 3D printing technology without facing severe logistical or financial challenges (Mohammed 2016). Size is another benefit of 3D-printed corals over other man-made structures. They may be positioned inside the reef framework without significantly changing the reef environment, such as light and water circulation, because of their tiny size (in comparison to other structures).

Other manmade structures, on the other hand, are frequently built in sandy regions that don't offer the same natural circumstances that fish typically encounter in a reef. This is done out of need. Due to its manageability, 3D-printed corals may also be used in manipulative experiments to test realistic conservation hypotheses and to replicate the distribution, dispersion, and abundance patterns of the coral of interest in nature it explain in figure 2.13. As predicted, the more complex corals had the greatest concentration of fish (Pagán and Mercado-Molina, 2018).

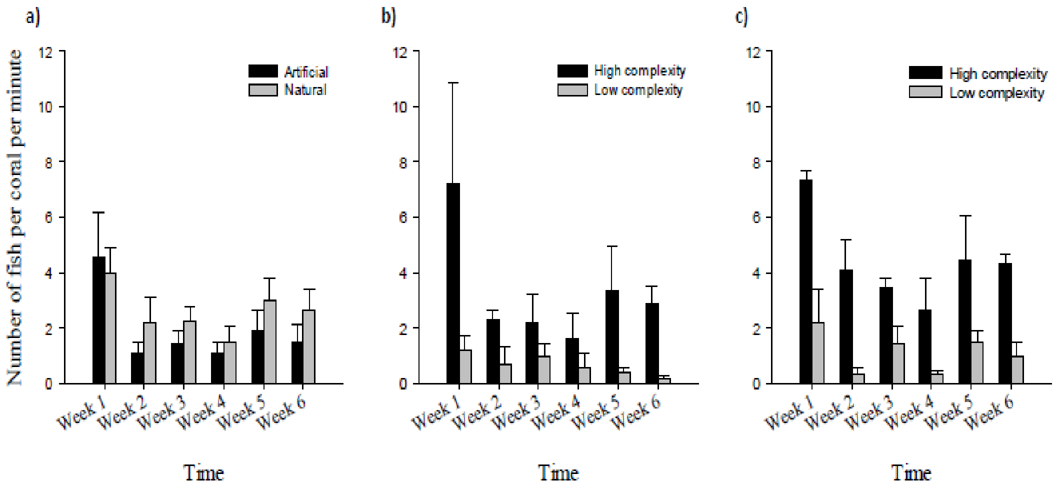


Figure 2.13: a) artific ial and natural corals b) high and low complexity artificial corals c) high and low complexity natural corals

Source: (Pagán and Mercado-Molina, 2018) Pagán and Mercado-Molina, 2018)

This finding backs up the idea that complexity plays a significant role in controlling fish abundance in coral reef ecosystems (Sherman et al. 2002; Gratwicke & Speight 2005). This is likely because complex environments minimize the danger of predation and competitive interactions (Almany 2004, Grabowski 2004). Higher coral complexity may boost species richness and biomass in addition to increasing the number of fish (Rilov & Benayahu 2002). Therefore, when intended for restoration and conservation initiatives, artificial corals should be built to be as intricate as reasonable. For instance, using 3D printing technology, an artificial A. cervicornis coral with a branching index of at least three may be produced in around five hours. This would need six to twelve months using conventional coral farming techniques (Hernández-Delgado et al. 2014). However, more study is required to increase the methodology's robustness. When importing digital photos of coral colonies with a branching index greater than 3, the Aegisoft Photoscan tool encountered a recognition problem and was unable to reconstruct a 3D model. With more recent technology than the researchers had available, this issue may be resolved. The photographs' definition and quality should also be improved.

Images of coral formations, for example. A more accurate depiction of coral can be achieved by detailing the branches and polyps (Pagán and Mercado-Molina, 2018). The application of 3D printing to conservation work is still in its infancy. Therefore, there are still many unanswered questions. Analyzing the effects of using ABS plastics in the marine environment is one of the most crucial of these. There is sadly little research examining ABS's impact on the biology and ecology of marine creatures. In addition to luring fish to the reef, artificial corals built of ABS material could operate as a substrate for the colonization of real corals and non-coral species. To fully comprehend the potential of these organisms to improve the conditions of fish populations in damaged reefs, it is imperative to determine whether 3D-printed corals can also promote fish recruitment and whether the rates of fish recruitment are sufficient to support local population growth and Figure 2.14 provides a visual summary of the fish population. In research with an improved spatiotemporal resolution, the function of 3D-printed corals in fostering reef biodiversity should also be more thoroughly investigated. Nevertheless, this research offers preliminary evidence that creating artificial corals using 3D printing technology may be a potential strategy to support efforts to conserve and restore coral reefs (Pagán and Mercado-Molina, 2018). This section describes three projects that have been conducted on reforming coral reefs. Some have succeeded and some are yet to be succeeded. However, each project helps to build a better solution for this study such as some of the structures have been made from plastics that are not eco-friendly. The design of some structures has caused longer periods to reform corals and creating coral lookalike structures is more complex. After gathering all the drawbacks and advantages of the study, it has been concluded that the best material to reform coral is concrete. Also, the use of concrete should be as eco-friendly as possible.

Surface roughness is beneficial for coral growth, particularly by enhancing coral larval settlement and survival. Research indicates that substrates with increased surface complexity, such as millimeter-scale roughness, significantly improve coral larval settlement compared to flat surfaces. For example, one study highlights that rough surfaces can increase larval settlement rates by an order of magnitude (arxiv.org, 2022). Furthermore, structural complexity is shown to boost not only larval attachment but also survivability of coral spats (MDPI, 2022). Computational simulations support these findings, demonstrating that millimeter-scale ridged topographies increase coral settlement rates in dynamic, wave-driven environments (arxiv.org, 2023). These results underscore the importance of surface roughness in creating optimal conditions for coral larvae, which is vital for coral reef restoration and conservation (arxiv.org, 2022).

2.10 Concrete for Coral Module

For a variety of reasons, concrete is the preferred material for usage by most reef managers. First, it is a substance that resembles real coral limestone in composition and is widely accessible, strong, heavy, and inexpensive. Concrete is incredibly versatile and durable underwater. It can be molded into almost any size or shape. According to some detractors, trace metals present in concrete, also known as Portland cement, can lead to coral sickness, however, in our experience, corals cling to these structures and never suffer this in the water. The biggest disadvantage of employing concrete is that, with the limited resources that most small reef managers have at their disposal, structures can rapidly become too heavy to install. Buoyancy World, Mini Square, the DMCR Cubes, and other of our major concrete projects were only made feasible because of agreements with the government, which gave us access to big barges (Artificial Reefs: What works and what doesn’t, 2022).

Use of concrete can be expensive and can cause various damages to the environment. Hence casting concrete should be sustainable and suitable for aquatic life. Since casting concrete is expensive alternative materials can be used. There are various alternative materials but using waste materials is the most sustainable solution. There are various wastes that can be used in concrete, and the next section describes them. Coral reefs thrive in specific conditions, and the concrete block should mimic those conditions as closely as possible. Among them, porosity was identified as a key factor (Subhan et al., 2019). The concrete block should be porous to allow water circulation and facilitate the exchange of nutrients and gases. Porous structures also provide a substrate for coral larvae to attach and grow (Subhan et al., 2019).

The utilization of foam to create foam concrete is a viable choice for improving the porosity of the modular concrete structure. Additionally, applying foam concrete can greatly reduce the weight of the concrete modules. This offers advantages in terms of material expenses, ease of handling, and lowered transportation costs. Coral reefs thrive in specific conditions, and the concrete block should mimic those conditions as closely as possible. Among them, porosity was identified as a key factor (Subhan et al., 2019). The concrete block should be porous to allow water circulation and facilitate the exchange of nutrients and gases. Porous structures also provide a substrate for coral larvae to attach and grow (Subhan et al., 2019). The utilization of foam to create foam concrete is a viable choice for improving the porosity of the modular concrete structure. Additionally, applying foam concrete can greatly reduce the weight of the concrete modules. This offers advantages in terms of material expenses, ease of handling, and lowered transportation costs. Coral reefs thrive in specific conditions, and the concrete block should mimic those conditions as closely as possible. Among them, porosity was identified as a key factor (Subhan et al., 2019).

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Foam concrete is a porous material formed by the uniform blending of pre-made foam and cement slurry, which subsequently undergoes a hardening process. This foam is created by introducing air or gas into a cement slurry, resulting in a lightweight, highly workable, and insulating material. Here are some key details about foam concrete: Foam concrete, also known as foamed concrete, aircraft, or lightweight cellular concrete, is a lightweight building material that consists of cement, water, fine aggregate (such as sand or fly ash), and stable foam. Foam concrete is a porous material formed by the uniform blending of pre-made foam and cement slurry, which subsequently undergoes a hardening process. This foam is created by introducing air or gas into a cement slurry, resulting in a lightweight, highly workable, and insulating material.

In the composition of foam concrete, various components are carefully selected to achieve desired properties. Portland cement serves as a fundamental ingredient, imparting strength, and durability to the mixture. To enhance both strength and workability, fine aggregates such as sand or fly ash are commonly incorporated. Water is a crucial element, forming a slurry when combined with cement and fine aggregates. A key component in the process is the foaming agent, introduced to create a stable foam. This foam, when integrated with the cement slurry, introduces aeration, and imparts lightweight characteristics to the concrete. The thoughtful combination of these elements not only contributes to the structural integrity of the foam concrete but also allows for the manipulation of its density and overall performance (Guide for Cast-in-Place Low-Density Cellular Concrete). The generation of foam in the foaming process can be achieved through diverse methods, with mechanical foaming, chemical foaming, or a hybrid approach being common techniques.

In mechanical foaming, air is introduced into the mixture through a foam generator or a dedicated foam generator machine. This method relies on mechanical means to create the desired foamy consistency. Chemical foaming involves the incorporation of a foaming agent into the mixture, leading to the formation of bubbles. The chemical reaction induced by the foaming agent plays a key role in generating the necessary foam. These distinct methods provide flexibility in tailoring the foaming process to specific requirements, allowing for customization in achieving desired foam characteristics in diverse applications (Guide for Cast-in-Place Low-Density Cellular Concrete).

2.11 Possibility of using waste for concrete

It is impossible to get rid of a lot of this garbage. Making more environmentally friendly use of this garbage, though, can lessen its impact. This is referred to as the "Waste Hierarchy." Its goal is to minimize, repurpose, or recycle waste recycling is the ideal method for getting rid of it. A sketch of the waste hierarchy is shown in Figure 2.14.

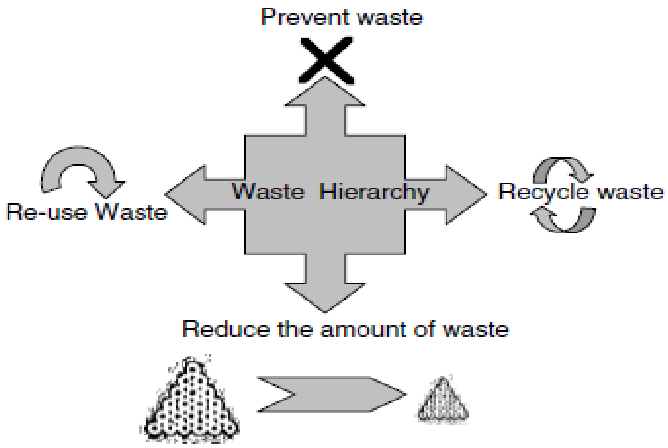

Figure 2.14: Waste hierarchy

Source - Batayneh, Marie and Asi, 2007

Materials classified as solid, infectious, or hazardous waste are not included in construction trash. Certain types of construction debris, such as those that contain asbestos, paint coatings made of lead, and lighting waste, may pose special health, safety, and environmental risks. These resources are not a part of this investigation. Research into creative and novel ways to repurpose waste materials is always developing. These research projects aim to fulfill society's need for trash disposal that is both safe and affordable. Utilizing recycled aggregates conserves natural resources and landfill space while promoting environmental cleanliness. The focus of the current study is on those waste products, notably glass trash, plastic waste, and building construction waste that can be utilized to replace more traditional ingredients, namely aggregates, in mixes for ordinary Portland cement concrete (OPC).

The issues with natural aggregate quarrying and the disposal of old concrete can be resolved by recycling concrete as aggregate. Numerous research investigations were carried out since these alternatives need comprehensive examinations to determine how they affect the characteristics of concrete. Wilson (1993) investigated how the qualities of concrete mixtures were impacted by the crushed concrete's uneven surface. Numerous research projects have looked at the usage of glass and plastic materials in various civil engineering applications. (Chanbane et al., 1999; Rindl, 1998; Shayan et al., 1999). Waste glass may be used for various purposes, including concrete aggregate, asphalt paving, and road building aggregate, according to Rindl (1998). Finite element analysis was used to do a parametric analysis. Based on their analysis, they concluded that using harder cement mortar if the concrete has a high strength or using softer cement mortar if it has a high can increase the strength of rubberized concrete by reducing the maximum rubber chip size, using stiffer coarse aggregate, employing uniform coarse aggregate size distribution, and more. In addition, they concluded that for practical usage, rubber chip content should be kept within a specified range. Crumb rubber was employed by Sukontasukkul and Chaikaew (2006) to swap out the coarse and fine particles in concrete pedestrian blocks.

This led to softer blocks, which gave the surface some softness. Additionally, crumb rubber blocks fared quite well in tests of abrasion and skid resistance. In 2004, Krammart and Tangtermsirikul investigated the usage of waste calcium carbide and bottom ash from municipal solid waste incinerators as cement raw materials. They discovered that the cement made from raw materials comprising spent wastes had a chemical makeup identical to the control cement. They also noticed that the newly made cement performed better in the sodium sulfate solutions than the control cement. Even though many academics have looked at the reuse of some waste materials in concrete, poor nations like Jordan have seen very little amount of reporting, data collecting, and study on these topics. The major goal of this study is to examine how the OPC mix performs when recycled waste materials, such as glass, plastic, and crushed concrete, are used in place of some of the mix's aggregates.

This will be proved by practical laboratory testing, in which crushed concrete will be used to replace a certain proportion of the coarse particles in OPC concrete, and fine glass and plastic aggregates will be used to replace a certain percentage of the fine aggregates (sand) (Batayneh, Marie and Asi, 2007). Out of the alternatives or wastes mentioned in the section use of ceramic waste is the most appropriate solution to cast some concrete to deploy in sea as its lack of hazardous materials compared to other wastes mentioned above.

2.12 Ceramic waste for concrete

The marked upsurge of economic and industrial growth has contributed to the well-being of citizens with an improved quality of life. Despite the European Community, national, and regional levels' efforts to control and regulate waste management following sustainable development policies and the Kyoto Protocol, an increasing amount of industrial, construction, and demolition waste is being produced. This has made w1aste management a serious issue. The promotion of resource recovery systems (reuse, recycling, and waste-to-energy systems) as a means of utilizing the resources contained in waste, which would otherwise be lost, could be used in waste management to lower the detrimental effects on the environment are specific actions aimed at preventing the generation of waste. Waste from the kiln industry where the endothermic decomposition reactions take place or else recovery of previously incorporated energy during production could be the advantages gained in terms of energy through waste management (Juan et al., 2010). Ceramic waste originated from two sources and the majority from the ceramic industry. Ceramic clusters with the companies belonging to the same or other sectors located in geographical proximity which enables the ceramic sector to attain a state-of-the-art level of progress and technological innovation globally.

The scale of production within the subsectors in the European Union and Spain follows the same trends, where the production of wall and floor tiles represents the highest percentage of the total, followed by bricks and roof tiles, and finally with other subsectors as represented on Figure 2.15 (Juan et al., 2010).

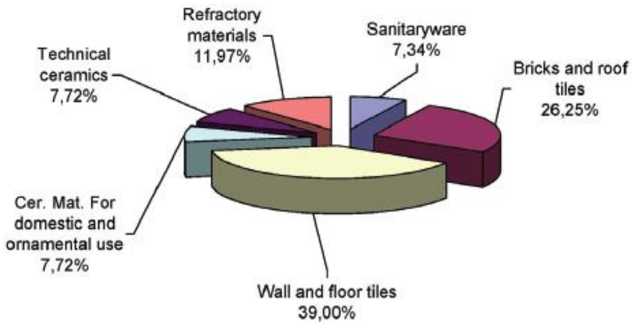

Figure 2.15: Construction waste amounts

Source: Juan et al., 2010

Natural materials containing high portions of clay minerals are used to produce ceramic products. Dehydration and controlled firing at temperatures between 700oC and 1000oC are the processes used to acquire the characteristic properties of the fired clay. Waste from the ceramic industry is not sorted into groups due to the reason for rejection which could be breakage or deformation and firing defects. 200 million tons of rubble is produced in the European Union (EU) and 40 million tons from Spain which is an equivalent of 2kg per inhabitant per day (A much higher figure than that for domestic waste) according to the Spanish National Plan for Construction and Demolition Waste result of the construction and demolition of buildings. 95% of construction waste in the Netherlands, 45% of construction waste in England, and 87%of construction waste in Belgium are being recycled. 28% of construction waste is recycled in the European region. 17% of ceramic waste is used in making concrete.

Approximately 10% of construction and demolition waste in Spain is recycled mainly used for road subgrade and subbase. The stony fraction and the rest are the two principal fractions of the construction and demolition waste. The most important fraction, the stony fraction comprised of ceramic materials (bricks, wall tiles, sanitary ware, etc.), concrete, sand, gravel, and other aggregates.

2.13 Types of ceramics in construction

Ceramics are a common building material comprised of a combination of minerals, usually silica sand, a clay binder, certain impurities, and up to 30% water. To create a glassy material with better density, strength, hardness, resistance to chemicals and frost, and greater dimensional stability, they are burned at a higher temperature than bricks. Water is forced out during firing, although this can be decreased from 30% to 2–5% by drying before firing.

Depending on the ceramic and the process specifics, items are molded as a powder at this low water content before being fired for days or weeks at 1,800–2,000 degrees. These materials are affordable in terms of maintenance expenses since they are ecologically stable and won't further oxidize in the atmosphere. When they are mixed with other materials, usually fasteners that are extremely strained and prone to corrosion, problems are likely to arise. If repairs don't work, the outcome can be shocking. Ceramics do not exhibit ductile behavior as metals do. They break down in a brittle way just after reaching their elastic limit (Use of ceramics in construction, 2022).

- Terracotta

This is "burnt soil." Between brick and vitrified wall tiles in uniformity and fineness, it is constructed from yellow to brownish-red clays. Unglazed chimney pots, air bricks, copings, and planters are frequently made of terracotta.

- Faience

This is terra cotta or stoneware in glazed form. Before glazing and refiring, the base material may be burned to the "biscuit" stage, or a "once-fired" technique may be utilized. The latter decreases the palette of colors accessible while improving the glaze's resilience to crazing (the development of lines or fissures on the glazed surface)

- Stoneware

This has a similar chemical make-up to fireclay but is burnt at a greater temperature and has a larger glass content. It becomes tougher and less absorbent as a result. Stoneware no longer has to be glazed to be used for drainage pipes thanks to modern production techniques.

- Earthenware

The basic components are mixed and may include a sizable amount of limestone. It serves as the body for table "China" and glazed wall tiles and is a finer product than stoneware. However, because of the potential for up to 15% water absorption, vitreous China is a better option for sanitary ware.

- Vitreous China

Since it contains more glass than earthenware and only absorbs around 0.5 percent of water, it may be used for sanitary fittings. It is more durable than earthenware.

- Porcelain

Porcelain and vitreous China are quite similar; however, porcelain is frequently produced using purer ingredients under tighter controls. It is employed for unique purposes like electrical insulators.

- New ceramics

Additionally, known as "technical" or "engineering" ceramics. Since they don't use raw clay that is dug from the ground, their purity is far higher than that of conventional ceramics. Powders are created, which are subsequently shaped by casting, pressing, extruding, or molding. Organic binders may be used to set the powders. The extremely high strength of these materials is ensured using pure components and meticulous production methods. There are various types of ceramic waste. But the major parts of waste come from ceramic tiles. More specifically ceramic glazed tiles. Therefore, the next sections describe how these ceramic glazed tiles are extracted and what kind of procedures led to extracting the waste, etc.

2.14 Ceramic glazed tile waste

Ceramic glazed tiles produce a large sum of waste all around the world. It is important to discuss how these tiles are produced and what part will generate waste.

Ceramic Tile Production

The processes of ceramic tile production could differ according to the final product required. The basic processes of producing ceramic tiles are as, Clay preparation, Forming or molding of the tile, Glaze preparation, drying, glazing, and decoration of the tile, Kiln firing, Classification, and packing. The detailed schematic process of producing ceramic tiles is represented in Figure 2.16 below. Clay granulates of tiny hollow spheres usually referred to as atomized clay form the product after atomization. (Framinan, Leisten, and Ruiz, 2014). Glaze preparation is another process that is contracted by third companies and glaze is made up of fruits and pigments. Single kiln firing is the most common process among all the processes. The ceramic tile production process starts with molding or forming ceramic tiles, and the rest of the process is automated in ceramic tile production plants. The mold dictates the physical dimensions of the tile, known as the time format. The visible side of the tile may not always be flat, but it has a pattern on it that resembles stone that was created by the mold's plate. Bisques should be further dried after shaping because they are delicate. Drying is done in dryers that are either vertical or horizontal (Small kilns). The bisque is made such that it resembles a chocolate bar and is sturdy enough to withstand other operations. Some ceramic or bisque tiles will not receive glazing decoration after being decorated with glaze lines (Which is not very common). During glazing, tiles are moved on a conveyor belt while various applications, embellishments, and other processes are carried out over them. Commonly employed for glazing are straightforward bell or glazing waterfall devices that advance random rotatory embellishments known as rotor hues. Modern glazing technology uses printers to imprint a wide variety of colors, patterns, and embellishments on ceramic tiles. More than 50 machines, some of which might be more than 50 meters long, make up glazing lines. Different glazing coatings affect the tile's design, color, surface, and other qualities.

The finished decorated ceramic tiles are kept in large boxes called roller stillages that have a lot of roller planes and are fed with bisques that have been saved and retrieved from subsequent stages. Automated guided trucks deliver large boxes containing glazed tiles to a storage location in the middle (AGVs). Firing in a single kiln is the primary manufacturing step. Large horizontal furnaces called ceramic kilns often have a single plane of rollers that move in a single direction to transfer the glazed bisques through the various phases. The temperature curve within the kiln is variable for each type of clay and tile. The temperature within the kiln is also influenced by the size or format of the tile. The tile must go through a variety of physical and chemical treatments to harden and finish. The top of the tile is fused and made harder by the glaze, giving it the ideal properties of a ceramic tile. AGVs then move fired tiles to a temporary storage location.

The final phase in the manufacture of ceramic tiles is classification and packaging, and various classification and packaging lines are frequently offered as the next step. Tile quality is checked visually or automatically by machines. The number and significance of the tile flaws determine whether it is first- or second-quality or if it should be thrown away. Due to diverse raw materials and a complicated production process, the tiles won't have the same tonality and physical dimensions (Calibers). As a result, tiles are divided into various batches, each of which is of the same grade, quality, and tone. Tiles are being moved on pallets and in boxes for delivery (Framinan, Leisten, and Ruiz, 2014). Modern ceramic tile manufacture includes additional polishing operations to achieve a stone or mirror quality, the rectification of the tile's edges, and optional cutting processes to create specific components like edges or reliefs.

It is also feasible to add more intricate embellishments and fire another round. From the beginning to the finish of the production process, the product is seldom ever handled in today's production facilities. As a result, the tiles may be made for a reasonable cost due to the process automation, businesses have made significant investments to produce tiles in massive quantities more efficiently. The kiln is the piece of ceramic tile production equipment that costs the most. The number of kilns at a factory for small- and large-scale ceramic tile production varies from two to three. Due to equipment depreciation, unit costs must be kept to a minimum, hence machinery utilization should be increased.

The process is clearly illustrated in Figure 2.16. It is common for manufacturers to sometimes shut down continuously operating kilns for maintenance. This results in reducing the make pan, which was the main goal selected for the model (Framinan, Leisten, and Ruiz, 2014).

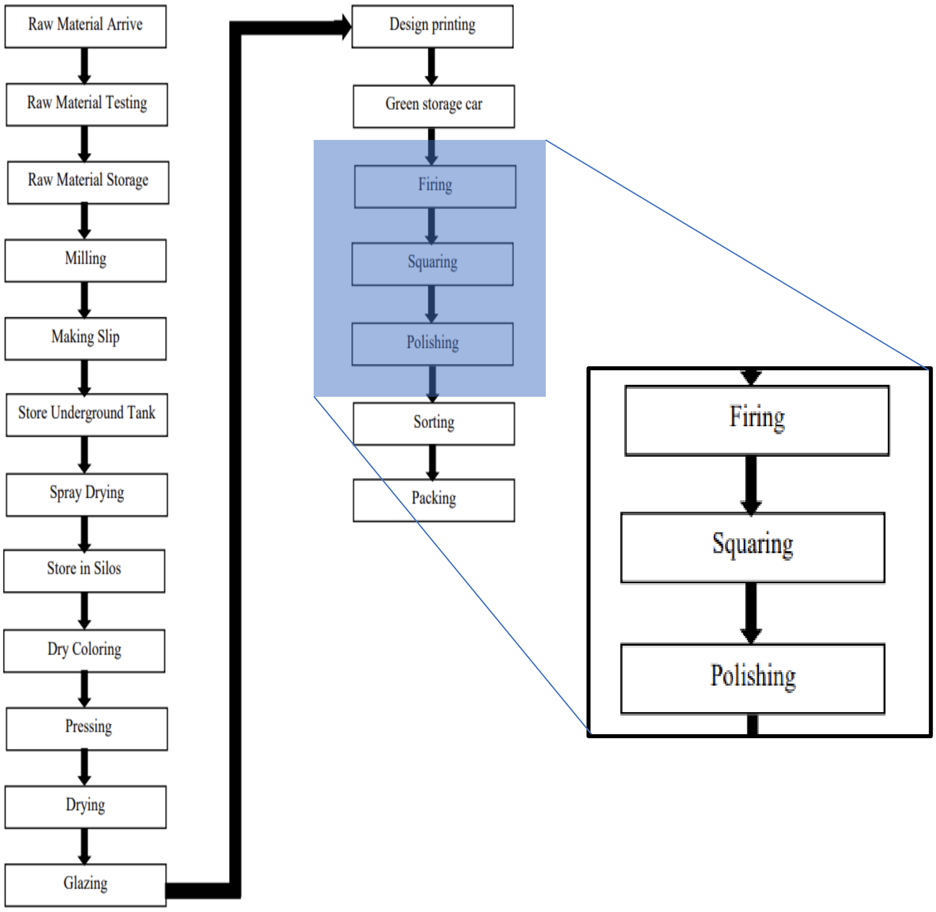

Figure 2.16: Ceramic generation process

Source: Framinan, Leisten, and Ruiz, 2014

Ceramic tiles are typically considered inert and not biodegradable due to the firing process during production (Sarkar, 2019). The firing or kiln process involves exposing the raw ceramic materials to elevated temperatures, causing them to undergo chemical and physical transformations, resulting in a hardened, durable material. This firing process typically involves temperatures exceeding 1800 degrees Celsius, leading to the sintering of the ceramic particles and the creation of a solid, non-biodegradable structure. Following the firing process, ceramic tile waste is generated during the squaring and polishing stage, and this specific type of waste is a focal point in the research study.

2.15 Characteristics of Ceramic Tile waste aggregate

Conventional Portland cement which goes with BS standards, granite with a maximum particle size of 12.5 mm (about 0.49 in) and river sand with a maximum particle size of 4 mm, and ceramic waste as fine aggregate and porta potties were used in a study on ceramic waste aggregate concrete that was conducted in South Africa. Preliminary research revealed that granite and porcelain absorbed water at rates of 0.23 percent and 0.55 percent, respectively (Awoyera, Ndambuki, Akinmusuru, and Omole, 2018). Due to the crushing procedure and the brittleness of the CWA, they had an angular form and a surface roughness that looked harsher than fine aggregate sand and granite. For this experiment 9 mixes were cast including a concrete mix and 4 recycled concrete mixes with ceramic as a fine aggregate. Each mix's workability was evaluated using a slump test following BS EN 12350-2. Fresh concrete was initially poured into molds, and the exposed surfaces of the concrete samples were covered with a perforated waterproof covering for 24 hours to guarantee a homogeneous saturation condition in the concrete. The samples were then taken out of the molds and allowed to cure in water at a temperature of 2020C till the test age. Utilizing an ELE compression machine with a 2000 kN capacity, the strength was assessed while maintaining a loading speed of 0.2 $N/mm^2/s$ (Awoyera, Ndambuki, Akinmusuru, and Omole, 2018).

The results of the investigation show that this concrete's workability can be compared to the control material that was within the medium and high as depicted in the accompanying. Overall, the mechanical performance of the concretes was superior to that of the control concrete. Within the confines of the trials conducted for this study, concrete prepared using CWA instead of some of the natural aggregates can be regarded as a viable substitute for standard concrete. It is even more suited than traditional concrete in terms of strength (Awoyera, Ndambuki, Akinmusuru, and Omole, 2018).

2.16 Chapter Summary

This chapter addresses the initial two objectives of the study: firstly, an exploration of the production, applications, and potential reuse of ceramic glazed tile waste in the context of Sri Lanka; and secondly, an examination of the marine biological and geological environment along the Sri Lankan coastal area. In the marine biological aspect, the discussion covers various ecosystems, their distinctions, individual characteristics, marine ecosystems in general, and the specifics of coral reefs as ecosystems, including their structure and associated threats. The next focus involves the creation of coral structures using different materials.

Ceramic tiles are commonly acknowledged as inert and non-biodegradable due to the intense firing process they undergo during production. This process includes subjecting the raw ceramic materials to high temperatures, resulting in chemical and physical transformations that yield a robust and enduring material. Temperatures exceeding 1800 degrees Celsius in the firing or kiln process facilitate the sintering of ceramic particles, culminating in the formation of a solid, non-biodegradable structure. After the firing process, the squaring and polishing stage generates ceramic tile waste, a focal point in this research study where an alternative use was suggested for this waste material, which offers a more environmentally sound alternative to disposal, mitigating potential long-term harm to the environment.

3 MATERIAL DEVELOPMENT

3.1 Chapter Introduction

This chapter is sectioned into two parts Material development and Structure development. In structure development, the researcher discusses how the selected structures change from structures used in previous studies, how to approach the module systems, the manufacturing process, and how the structures should be implemented without harming the coral reefs.

3.2 XRD Test

X-ray diffraction (XRD) is an indispensable tool in the realm of materials science and beyond, offering profound insights into the atomic and molecular structure of crystalline materials. By directing X-rays toward a sample, XRD exploits the interaction between these high-energy waves and the electron clouds surrounding atoms within the sample. The resulting diffraction pattern, formed by the scattered X-rays, unveils crucial information about the arrangement of atoms within the crystal lattice. Through meticulous analysis of the diffraction pattern's angles and intensities, researchers can discern fundamental structural details such as atomic spacing, crystal lattice type, and orientation. This technique is pivotal for identifying crystalline phases, elucidating crystal structures, and assessing crystallinity levels in diverse materials, spanning fields from materials science and chemistry to biology and geology. The initial stage of the project is focused on the development of concrete. The first step was to conduct an Industrial survey investigating the ceramic glazed tile waste product. After the pilot survey, the identification of a suitable production company to obtain ceramic waste is done. 3 companies produce ceramic tiles in Sri Lanka. They are,

1. Company 01
2. Company 02
3. Company 03

According to the 1 Company Annual report, the tile-associated waste products are 14,433 MT in the year 2017-2018 The data is presented graphically in Figure 3.1

NATURAL CAPITAL	
	17/18
Materials (Mt)	181,574
Energy (Mn KwH)	47.2
Water (Mn litres)	129
Waste water (Mn litres)	94
Waste (MT)	14,433

Figure 3.1: Tile-associated waste products in Company 01 year17/18

There are three Ceramic tile waste storage units in Sri Lanka. Such as,

- Company 01 - Ranala
- Company 02 - Bandaragama
- Company 03 - Horana

Ceramic waste was taken from these three storage factories. The test was conducted to check the composition of heavy metals such as Lead (Pb) in ceramic waste. To recognize materials such as crystalline this test can be used. Also, it can be useful to get the data on unit cell dimensions. Such characteristics are recognized by whether they are finely ground, homogenized, or have an average bulk composition. The apparatus used for this test is an X-ray diffractometer. It consists of three parts a sample holder, an X-ray tube, and an X-ray detector. The process inside the cathode ray tube first creates a burning filament that makes electrons. These electrons accelerate with a voltage towards their target. It hits the target with its electrons that accelerate. X-ray spectra will be created when these electrons have sufficient energy to move the target inner shell electrons. These spectra have two components such as K1 and K2. K1 – Has twice as intense and a shorter wavelength compared to K2. These wavelengths will be used to identify substances like Copper, Ferus, Chromium, etc. To conduct the diffraction procedure, monochromatic X-rays should be created using foils or a crystal monochromatic.

Since K1 and K2 have the same wavelengths a weighted average of the two is employed. With a CuK radiation of 1.5418, copper is the most frequent target material for single-crystal diffraction. This sample will be intact with collimated X-rays. The intensity of these X-rays is measured when the detector and sample spin. This radiation is caught by the tool named detector and it will process the radiation. This signal will be transformed into a count rate and will be printed using the computer and printer. The geometry for the X-ray diffractometer is simply the spinning sample at such an angle in the direction of the collimated X-ray beam and the X-ray detector rotates at an angle of 2 to capture the diffracted X-rays. A goniometer is a device used to hold the angle and rotate the sample. For common powder patterns, data is gathered at fixed angles in the X-ray scan, ranging from 2° to 5° to 70°.

3.2.1 Case Study 1

- **Sample 01: Dry Squaring Waste Plant**

Small, unpolished tiles with dimensions of 30" x 30" and 40" are used in the squaring plant. These tiles are squared in secure spaces. When opposed to wet squaring, the quantity of waste eliminated during this operation is much less because it is carried out in a dry atmosphere. The tile is small, therefore there isn't a lot of trash created as a result. It is kept in an underground production room where several bags are gathered and kept on the company's property. Since it began a few months ago, it has been getting rid of around 3 tons of waste powder daily. This quantity could rise in the future as manufacturing operations expand. Used wastage of ceramic used in this experiment is dry. Characteristic of this dust is its fine white powder. Such features can be seen here in Figure 3.2. The major mineral assemblages via XRD analysis were identified as quartz, nontronite, gismondine, and anorthite. The counts in the figure show the intensity.

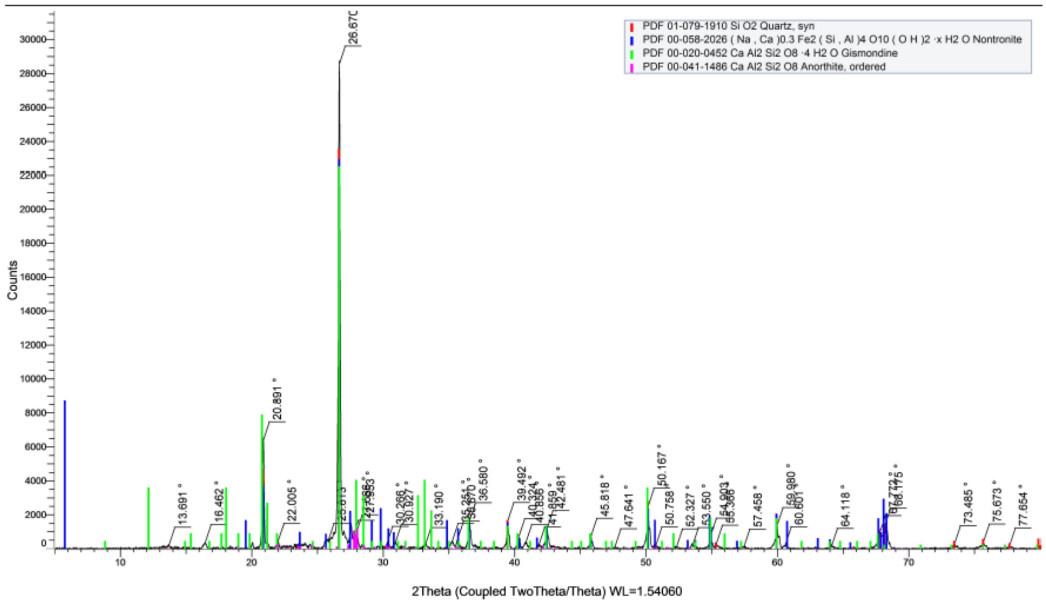

Figure 3.2: X-ray Powder Diffraction (XRD) for Sample 1

- **Sample 02: Wet Squaring Waste Plant and Polishing Plant**

Another tile-squaring facility may be found at the Company 01 complex. Large ponds are located far from the factory where the water is taken from the plant and the polishing plant is discharged as shown in Figure 3.3. Alum is used by the ceramic components that enter the pools from the west to swiftly deposit the bottom. The water flows through five pools located one after another. Alum is used to deposit powdered ceramic debris into the pool's bottom. The distinction is that as the component Components migrate from the first pool to the last pool, their weight fluctuates. The first pool receives the heavier ceramic particles, while the last pool receives the lighter ones. The residual ceramic water is sent through the filter press in the last pool to separate the ceramic from the water. The cleaned water is sent to the water treatment facility where it is used for additional tasks including polishing and squaring. The leftover ceramic tile from these pools is scattered throughout the building and in sizable courtyards. This ceramic tile waste varies from dry squaring waste, which aggregates and turns into a brownish liquid due to the alum's activity. Key points found in this test are,

- Gray liquid visibility
- Sand particles and clay particles of different sizes

- Admixtures weren't used during the mixing but in the polishing procedure, some chemicals were used. The major mineral assemblages via XRD analysis were identified as quartz and gismo dine.

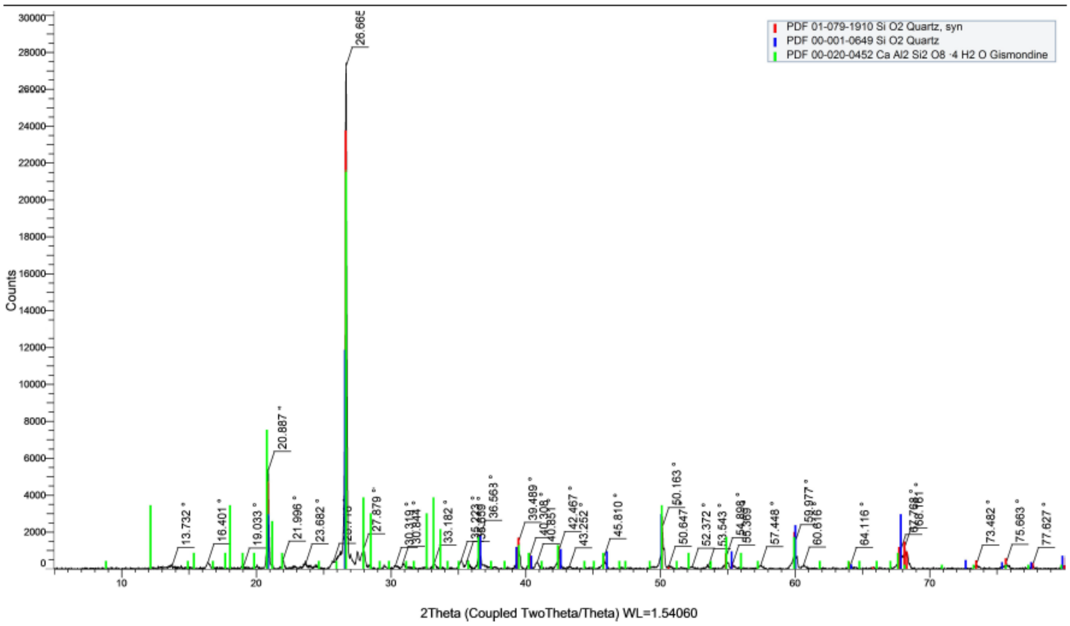

Figure 3.3: X-ray Powder Diffraction (XRD) for Sample 2

3.2.2 Case study 2

- **Sample 03: Wet squaring, polishing, and glazed line waste**

This also functioned as a separate collection point for the waste generated by Company 01, Squiring, and polishing operations. However, the capacity is little, and when it goes over the cap, it enters the main tanks. There, ceramic garbage is gathered. The unique aspect of this situation is that the glazing trash was also gathered in the same tank. 6900 MT of filter cakes discharged from here on 18/19. That amounted to 75% of the total garbage produced. As shown in Figure 3.4 This trash has a murky appearance. Due to the great distance from the waste containers, most garbage is dumped in the sewer. Grace adds murky color to the white or gray tone. Here, trash from the production process is not recycled, and waste produced by the filter press is kept separately.

Damaged tile fragments are ground into tiny bits and delivered to a different plant to produce wall block bricks. A little filter cake is also used, although most of it is dumped at ball mining centers' landfills. Lages via XRD analysis were identified as quartz, Neuburg siliceous earth, kaolinite 1-A, and albite.

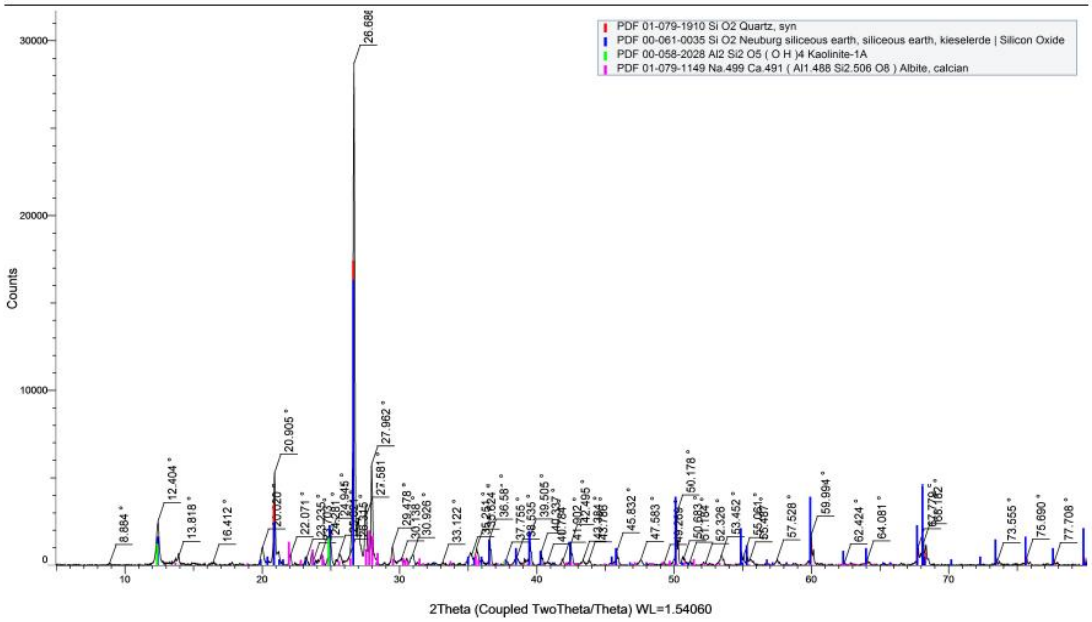

Figure 3.4: X-ray Powder Diffraction (XRD) for Sample 3

3.2.3 Case Study 3

The sample used in this process is comparable to the dry squaring waste from Company 01. The manufacturer performs all the squaring onsite rather than wet squaring equipment. Additionally, the Company 1 produces its large-scale tiles in an open environment. In a nearby yard, a ceramic powder that has been abandoned is dumped. Every day, about 6 tons of garbage are produced. The exterior characteristics resemble those of sample 4 Illustrated in Figure 3.5. The major mineral assemblages via XRD analysis were identified as quartz, nontronite, bustamite, and albite.

- **Sample 4: Dry Squaring Waste Plant**

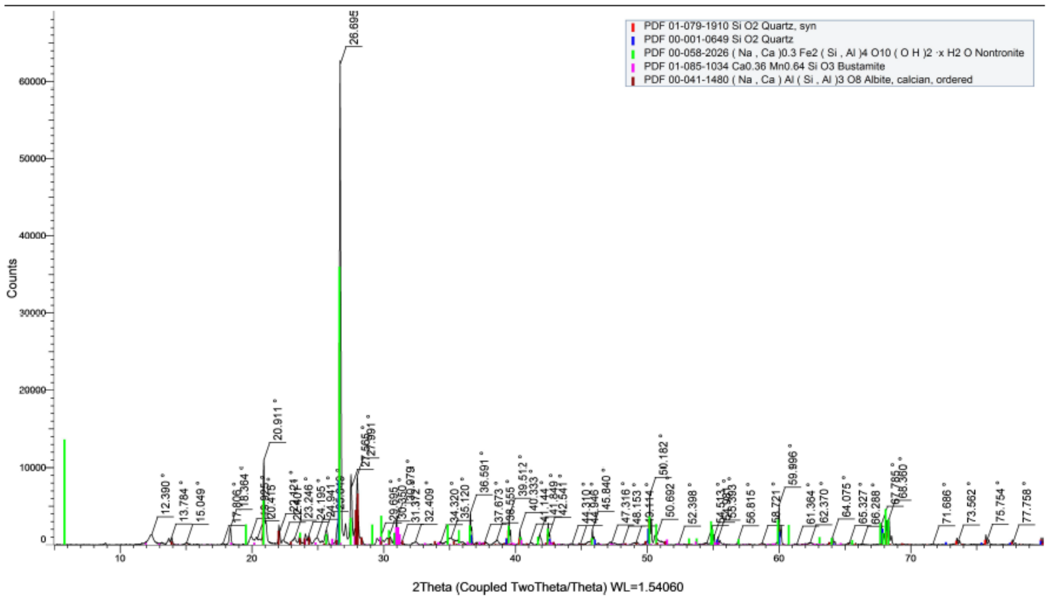

Figure 3.5:X-ray powder diffraction (XRD) for Sample 4

3.3 Sieve analysis

The sieve analysis test was done in August 2020. This test was conducted for ceramic tile waste, gravel, and sand. 4 tests were carried out for the four ceramic samples selected from the companies. Figure 3.6 shows the retaining percentages compared to the sieve sizes for 4 samples and used sand and gravel analysis. Sample curves have a similar pattern to sand compared to gravel. So, the ceramic waste is used in the concrete mix as a fine aggregate. Out of the four samples, samples 1 and 2 have a similar pattern to sand. So out of the two samples, Sample 2 is selected to put in the concrete mix with sand.

The ceramic tile waste was obtained from the wet squaring waste plant. The sieve analysis test confirmed that a major part of the fine aggregate is the powder passing through the 125 μm filter with a weight of 75g of the selected sample. Preliminary investigations were directed at the aggregates following BS 882 to determine their suitability. The data is presented graphically in Figure 3.7.

Figure 3.6: Used sieves and ceramic waste inside a sieve

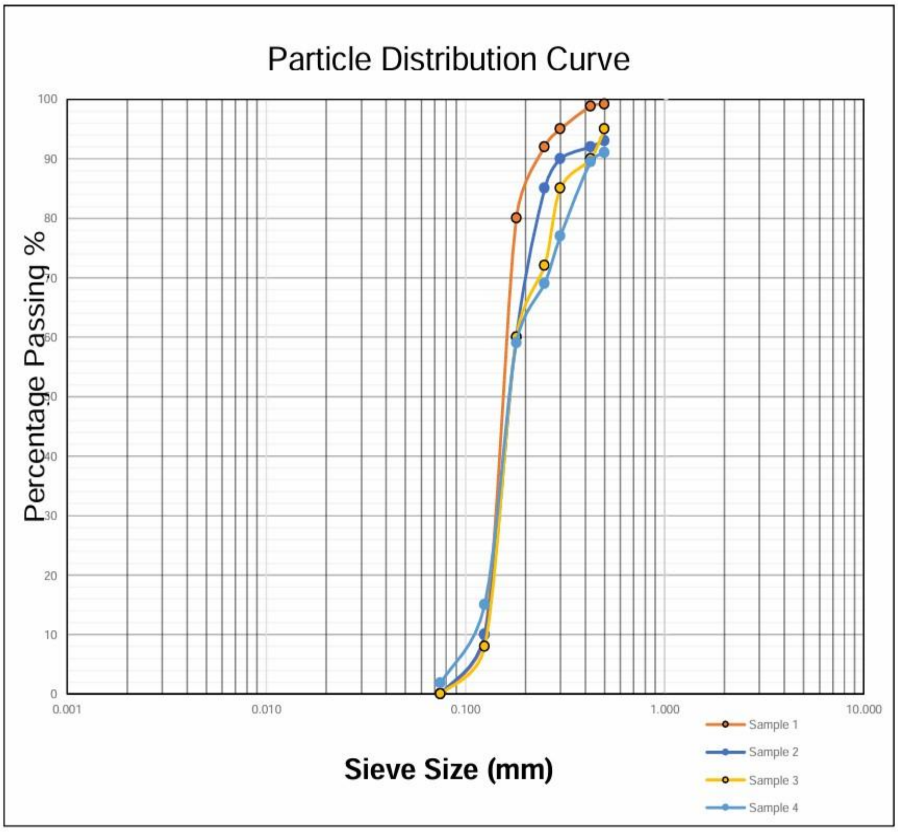

Figure 3.7: Grain size passing curve similarities with sand and gravel

3.4 Mix Design

A mixed design based on BS 5328 with M1 - M5 was achieved with the use of cement, water, and aggregates. There, the fine aggregates were replaced with varying percentages of ceramic tile waste at 25%, 50%, 75%, and 100%. In each mix, nine 150mm x 150 mm x 150 mm sized concrete cubes were produced, and the total was 45 cubes. The water-to-cement ratio varied from 0.5 – 1.1 to achieve the required workability yet no admixtures were used for the mixing.

Then the materials were mixed in a mechanical mixer. In M1 the ceramic dust has only been used for 25%. In M2 where the dust is 50% increased, there is no workability. In M5 and M6 there is no workability. Table 3.1 provides a visual summary of the Mix design Ratio..

Table 3.1: Selected mixed design ratios considering weights

Mix Designs	Materials			
	Cement	Fine Aggregates		Coarse Aggregates
		Ceramic Tile Waste	Natural Sand	
M1	1	0.5	1.5	4
M2	1	1	1	4
M3	1	1.5	0.5	4
M4	1	2	0	4
M5 (Standard)	1	0	2	4

3.5 Slump test

A slump test was conducted in a laboratory using the selected sample concrete as shown in Figure 3.8. Most of the concrete mixes had zero workability for 0.5 – 0.7 water-cement ratios. Figure 3.8 shows the produced slumps for each mix. Some slumps indicate zero workability in the figure. A slump test was performed according to the BS EN 12350-2 for the prepared concrete before the molds are filled with concrete for the cube test.

Figure 3.8: Selected concrete mix design

According to the supervisor's instructions, the water-cement ratios were taken starting from 0.5 to 1.1 as presented in Table 3.2 the sand waste portion for fine aggregate in M1 is 3:1. For all the ratios mentioned there were slumps. However gradually increasing the waste amount compared to sand the slumps were zero for some water-cement ratios.

The only mix design M 1 with Ceramic waste shows a slump value for water cement ratio 0.5 as per Table No: 05 Conventional concrete without the ceramic waste- M5 Therefore, the workability in low water-cement ratios is higher and Table 3.2 offers a summary of the Data.

Table 3.2: Slump test observations

CH No	Cement	Fine		Coarse	W/C Ratio	Slump (mm)
		Sand	Dust			
M1	1	1.5	0.5	4	0.5	10
					0.6	12
					0.7	28
					0.8	30
M2	1	1	1	4	0.5	-
					0.6	-
					0.7	10
					0.8	25
					0.9	40
M3	1	0.5	1.5	4	0.5	-
					0.6	-
					0.7	-
					0.8	15
					0.9	28
					1	40
M4	1	0	2	4	0.5	-
					0.6	-
					0.7	-
					0.8	-
					0.9	18
					1	32
					1.1	47
M5	1	2	0	4	0.5	45
					0.6	50
					0.7	60

Even though the water-cement ratio increases, it is proven that ceramic waste concrete can still be worked with a high slump; in other words, this sort of concrete requires more water to get standard workability. In M1, only 25% of the ceramic dust has been used. There is no workability in the 0.5 W/C ratio, In M2 Where dust increases up to 50%. But 0.7w/c was good workability as per our requirement three commercial ADMIXTURE was used in the experiments.

3.6 Cube test

Choosing the appropriate strength for concrete is crucial to guarantee stability and durability (Figure 3.10). In the case of an underwater block, the strength of concrete is influenced by factors like water pressure, marine exposure, and the intended purpose of the structure. In our study, we focused on a shallow sea area with a maximum depth of 5 meters. After evaluation, we found that M15 concrete with a strength of 15 MPa would be sufficient for this context. Therefore, we used a criterion to ensure that the developed material possessed a strength greater than 15MPa.

The cast specimens (cubes) were covered with polythene only to be removed from the mold when it was up to 24 hours and cured in water until their testing age of 28 days. The compressive strength was tested using a universal compression testing machine.

Figure 3.9: Conducting cube test in the lab.

In Figure 3.10, the graph illustrates the variation in compressive strength relative to the water-to-cement (w/c) ratio for different compositions of fine aggregate replacements (25%, 50%, 75%, and 100%) after 28 days of curing. Concrete mix 1 exhibits strength characteristics within water-cement ratios of 0.5, 0.6, and 0.7. Similarly, Concrete mix 2 demonstrates strength properties within the water-cement ratio range of 0.7, 0.8, and 0.9. For Concrete mix 3, strength properties are only within water-cement ratios of 0.8, 0.9, and 1. Concrete mix 4 displays strength properties within water-cement ratios of 0.9, 1.0, and 1.1. Lastly, Concrete mix 5 exhibits strength properties within water-cement ratios of 0.7, 0.8, and 0.9. Other w/c in the concrete mixture are unsuitable for comparison due to their insufficient workability.

The test results show that using ceramic tile waste as fine aggregate replacements increases the compressive strength of concrete compared to the compressive strength of normal concrete. It can be identified that the highest compressive strength was obtained when the natural sand was replaced by 25% (M1) from the ceramic tile waste having a value of 49.9 MPa with a W/C ratio of 0.5 Figure 3.12.

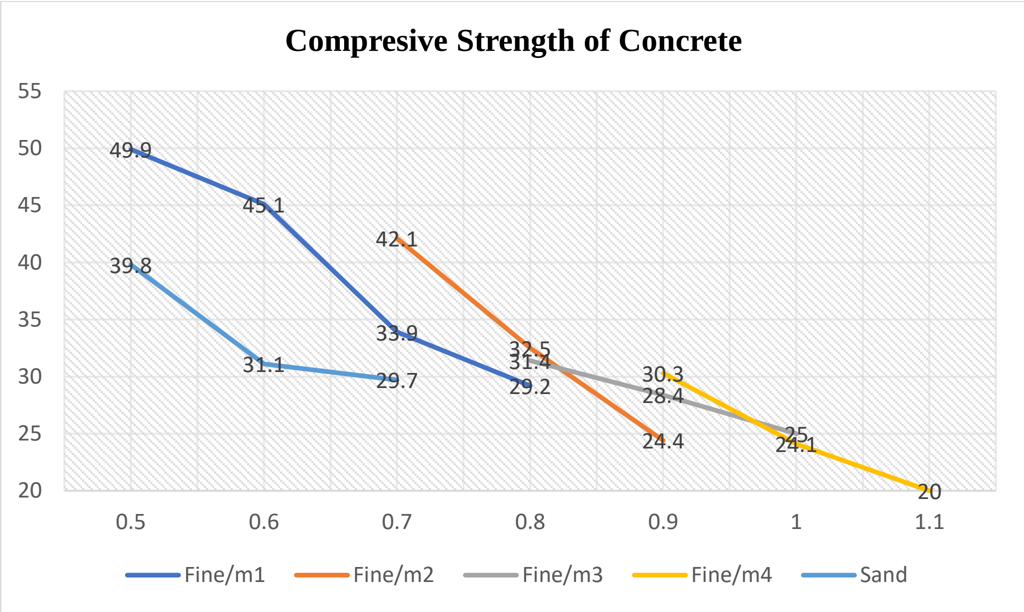

Figure 3.10: Variation of compressive strength against w/c ratios

Following these investigations, concrete modular units were fabricated using the developed foam concrete. These modular units were then positioned in the designated study area in October 2022. The focus of this research and thesis is limited to identifying an appropriate foam concrete mix for the proposed concrete modular units. In future research, the performance of these foam concrete modular units, situated in the study area, should be analyzed after allowing them to remain in that location for an adequate period

3.7 Optimizing Concrete Composition with Foam Concrete

Upon assessing the performance of concrete modular units within the study area, it became apparent that enhancing the material's porosity could positively impact coral growth by enabling increased water circulation and facilitating the exchange of nutrients and gases. This observation aligns with findings in related literature, which highlight that coral reefs thrive under specific conditions. Accordingly, it was noted while strength is important for stability and durability, other factors such as porosity, surface texture, and chemical composition play crucial roles in supporting coral growth.

The study utilized a 1:2:4 mix, replacing fine aggregates with ceramic tile waste. Results indicated that the optimal mix was achieved with a 25% replacement, ensuring structural integrity, environmental compatibility, and meeting the required strength of 25 MPa. However, testing revealed a significantly higher strength, exceeding 45 MPa.To further optimize the material, foam concrete was introduced to reduce weight and increase porosity. This modification was identified as the optimal composition for cost efficiency, weight reduction, and improved surface quality. The enhanced surface characteristics also demonstrated potential for promoting coral attachment, contributing to marine ecosystem restoration.

To support coral reef growth, concrete blocks must replicate the conditions in which coral reefs flourish. A vital factor Subhan et al. (2019) identified is porosity, which ensures water circulation, and nutrient, and gas exchange, and provides a suitable substrate for coral larvae attachment and growth. An experimental approach involving the use of foam concrete was implemented to enhance porosity. For this research, chemical foaming was used, and a detergent served as the designated foaming agent to produce foam concrete.

Foam concrete (FC) is a lightweight, cellular material formed by mixing base mortar with conditions, which results in the creation of closed air voids within the concrete. The primary components of FC are cement, sand, water, and foam, with additives like fly ash, silica fume, superplasticizers, and other performance-enhancing materials sometimes incorporated to optimize the mixture’s properties. The mix design of foam concrete is not standardized, and researchers often use methods like the target density method**,** proposed by Kearley, to determine the appropriate proportions of ingredients.

- Fresh State Characteristics

In the fresh state, FC is typically self-compacting and does not require mechanical compaction. The mixture needs to exhibit specific properties such as good rheology, consistency, and workability to ensure proper casting and avoid issues like foam burst during compaction. The water-to-cement ratio, the type and concentration of foam agents, and the use of superplasticizers or other additives play a significant role in achieving the desired fresh-state properties. To ensure the material flows into molds without segregation, tests such as the inverted slump test are used. For a mix to have good workability, the flow time should ideally be within 20 seconds, allowing the mix to be poured and self-sealed in the mold. The incorporation of additives, especially fibers, can slightly reduce the workability of the mixture by increasing viscosity due to fiber absorption of cementitious materials. However, with proper mix design, the use of fibers can still improve the workability by creating channels in the foam films, allowing better flow.

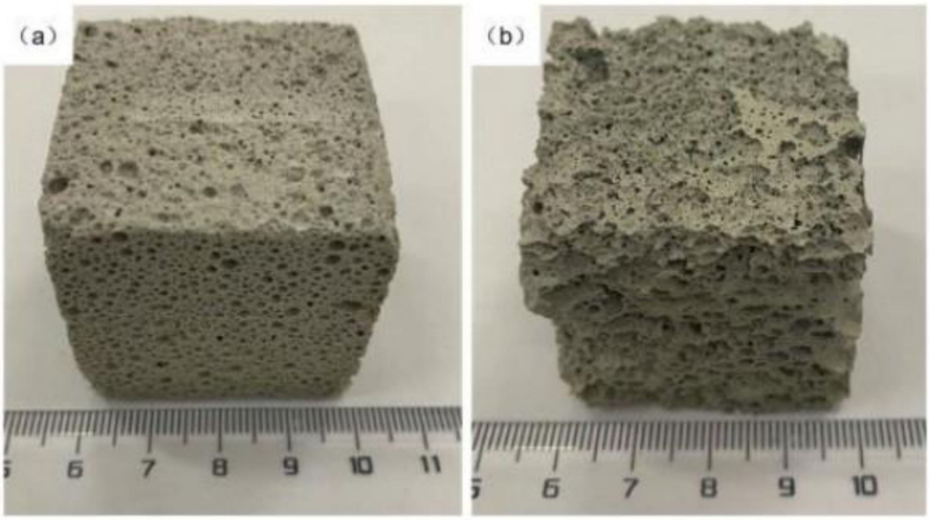

Figure 3.11: Air bubbles distributed in hardened foamed concrete; with (a) ternary and (b) binary or without aerogels

Source: Amran, Mugahed & Fediuk, Roman (2020).

Additionally, factors such as segregation and bleeding need to be carefully managed. Segregation refers to the separation of the components of the mixture, which can occur when too much water is present. By adjusting the water-to-cement ratio and using microfillers like finely ground limestone or quartz sand, the stability of the mixture can be improved, minimizing the risk of segregation and bleeding. Proper mix design can help maintain the integrity of the foam, ensuring the foam bubbles do not burst prematurely during the casting process.

- Hardened Properties

Once the foam concrete has cured and hardened, its mechanical properties become crucial for its performance in structural applications. In the hardened state, foam concrete exhibits lower tensile strength compared to compressive strength due to the entrained air voids. These air voids reduce the material's weight and provide excellent thermal insulation properties, which make FC ideal for non-structural applications like insulation, road embankments, and fill material. However, these same voids can limit the material's ability to withstand tensile and flexural stresses, which are critical for load-bearing structures.

Additives such as fly ash and silica fume can be incorporated into the mix to improve the strength of hardened foam concrete. These materials can improve the binding capacity and reduce the voids, thereby enhancing the material's compressive strength and overall durability. The density of foam concrete is a key factor that influences its mechanical properties, with lower densities generally resulting in lower strength but better insulation performance. By optimizing the foam content, adjusting the aggregate size, and using supplementary materials, the density and strength can be tailored to suit specific applications. The curing method also affects the hardened properties, with steam curing used in some cases to accelerate the setting process and improve early strength development.

Figure 3.12: Steps for preparing concrete cube samples

Overall, foam concrete offers significant advantages in terms of weight reduction, thermal insulation, and cost savings in construction. Its mechanical properties can be optimized by adjusting the mix proportions, incorporating additives, and carefully managing the fresh state characteristics. Despite its lower tensile and flexural strength compared to traditional concrete, it remains a highly versatile material, particularly for non-load-bearing and insulation applications. Further research into optimizing foam content, improving workability, and exploring new additives can expand the potential of foam concrete in more demanding structural applications.

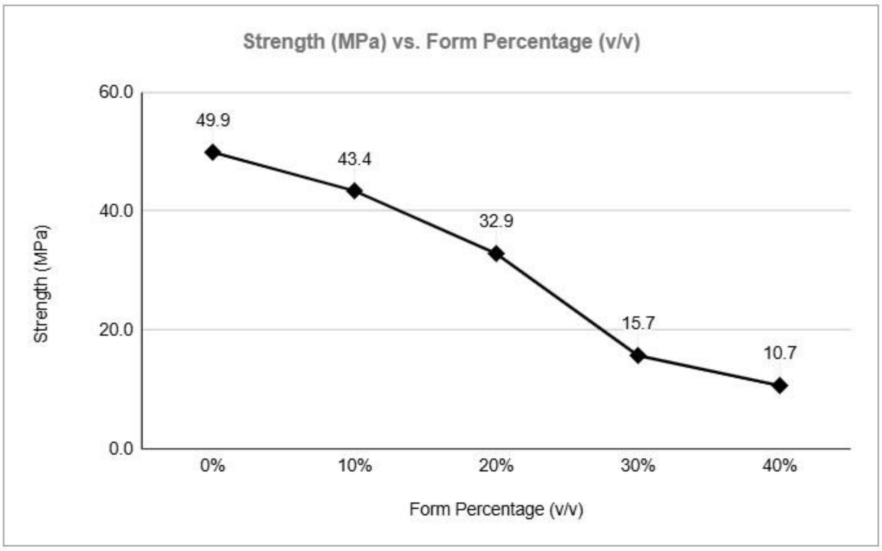

Figure 3.13: Strength vs Foam Percentage of the test cubes

Moreover, incorporating foam concrete can substantially reduce the weight of the concrete modules. This helps reduce material expenses and facilitates easier handling, ultimately leading to lowered transportation costs. Previously, it was established that incorporating ceramic tile waste as a replacement for fine aggregate enhances the compressive strength of concrete compared to regular concrete. The highest compressive strength was observed when 25% of natural sand was replaced with ceramic tile waste yielding a value of 49.9 MPa with a water-to-cement (W/C) ratio of 0.5. Hence, we employed a particular concrete mixture with a ratio of 1:1.5:0.5:4: for cement, , sand, and ceramic tile waste and coarse aggregate, respectively, to incorporate foam into the structure.

As suggested by Othman et al. (2021), it is recommended to maintain a target foam concrete density of 1600 kg/m³ while ensuring acceptable strength (Othman et al., 2021). Therefore, the criterion of 1600 kg/m³ was used for evaluation. Based on the density values of the test cubes provided in Table 3.3, it is apparent that the concrete mixtures with 20% and 30% foam percentages satisfy the specified density criteria. Then an analysis was conducted to assess the potential reduction in self-weight achievable through the utilization of foam concrete focusing on the percentage reduction in self-weight as shown in Table 3.3

Table 3.3: Weight reduction of concrete modular

Form Percentage (v/v)	Strength (MPa)	Weight of the Concrete Modular (kg)	Weight Reduction (%)	Cost of Concrete Modules (Rs per Kg)
0%	49.9	75.7	-	38.9
10%	43.4	73.4	3	34.6
20%	32.9	68.9	9	28.0
30%	15.7	65.4	14	18.9
40%	10.7	59.8	21	17.4

A 20% foam percentage leads to a 3% reduction in weight, while a 30% foam percentage results in a 9% reduction. Since a greater reduction in weight is preferable and considering that the 26% foam percentage satisfies both strength and density criteria.

Then the percentage of foam was varied, and its effects were analyzed on strength reduction and density reduction, with the latter contributing to a decrease in the self-weight of the concrete modular components. To determine the suitable foam percentage, five different foam percentages, representing variations in the volume of foam compared to the volume of the concrete cube, were selected. For each mix, three concrete cubes were cast. Following this, a cube test was carried out to confirm whether the strength requirements were met.

Cost Comparison of the proposed method

Figure 3.14 provides a detailed analysis of the impact of foam percentages on the strength, weight, and cost of concrete modular components. As foam percentages increase, the strength of the concrete, represented by the blue line, decreases due to the increased void content in the material. At 0% foam, the strength is 49.9 MPa, indicative of dense, traditional concrete. With a 10 % foam percentage, the strength reduces to 43.4 MPa, which still meets the specified criteria for modular applications. At 20% foam, the strength drops further to 32.9 MPa, approaching the lower acceptable limit for structural reliability. Beyond this, at foam percentages of 30% and 40%, the strength falls below 15 MPa, making these mixes unsuitable for structural or load-bearing applications.

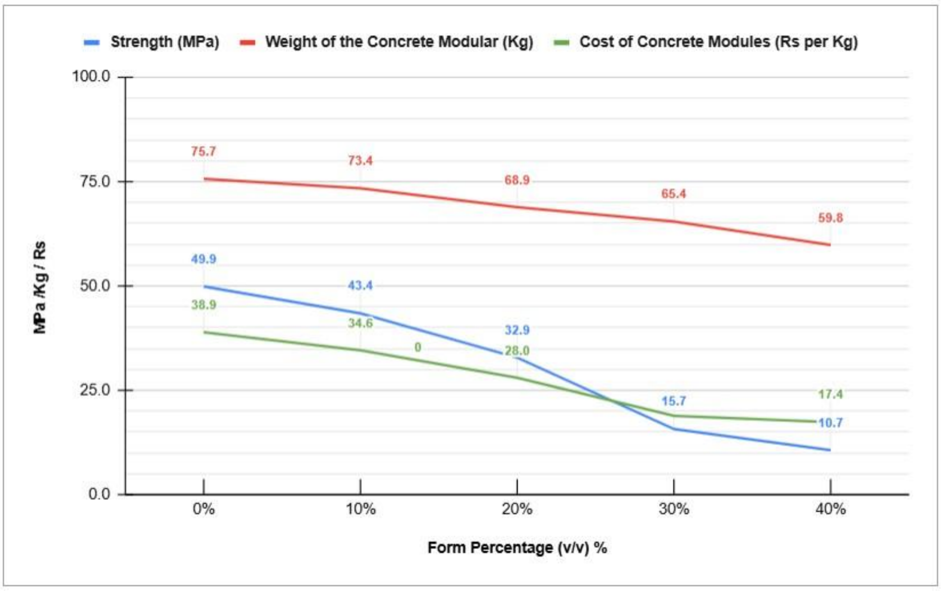

Figure 3.14: Form Percentage Vs Strength (MPa) / Weight of the Concrete Modular (Kg) / Cost of Concrete Modules (Rs per Kg)

The red line shows the weight of the concrete modular components, which decreases significantly as foam percentages increase. At 0% foam, the weight is 75.68 kg, representing dense concrete. At 10% foam, the weight reduces to 73.4 kg, achieving a 03% reduction in self-weight. At 20% foam, the weight decreases to 68.9 kg, corresponding to a 14% reduction. Although higher foam percentages (30% and 40%) achieve even greater weight reductions to 65.4 kg and 59.5 kg, respectively, these mixes are not viable due to the critical loss in strength. The 26% foam percentage offers substantial weight savings while maintaining adequate structural performance, making it an effective solution. The cost of concrete modules, depicted by the green line, decreases as foam percentages increase, owing to the reduced density and material usage. At 20% foam, the cost per kilogram is Rs 28, representing an economical and efficient mix that balances weight and strength. At 30% foam, the cost decreases further to Rs 18.9 per kg, but the marginal cost savings are outweighed by the notable reduction in strength. Higher foam percentages offer further cost reductions but are unsuitable for structural applications due to insufficient strength.

Based on the analysis, the 26% foam percentage is the most suitable choice for coral modular applications. It achieves a significant 20% reduction in self-weight, reducing the modular weight from 75.68 kg to 67.5 kg, while maintaining a compressive strength of 25 MPa, which satisfies the required strength criteria. Additionally, the cost of Rs 23 per kg is competitive and provides an economical solution for large-scale applications. While the 30% foam mix offers slightly greater weight reduction and marginal cost savings, the associated drop in strength makes it less suitable. Foam percentages above 30% are entirely unsuitable due to critical strength losses, despite their lower weight and cost. Thus, the 26% foam percentage provides an ideal balance of strength, weight reduction, and cost efficiency, making it the optimal selection for lightweight, durable, and economical concrete modular designs.

- **Cost of the proposed Project**

A comparison was made between the costs associated with the proposed concrete plates and hexagons. The analysis considered the manufacturing and placement of 1000 pieces of plates and 500 pieces of hexagons, and the corresponding costs are detailed in Table 3.4 below. Notably, utilizing ceramic tile waste in this context results in a cost saving of Rs. 180,959 representing a significant portion of the total expenditure of Rs. 1.7 million. However, by using Form Concrete, the total cost drops further to Rs. 1.2 million leading to an overall savings of Rs. 455,643 compared to conventional concrete.

Table 3.3: Comparison of Costs for Concrete Plates and Hexagons with Ceramic Tile Waste Utilization

Description	Amount (Rs) without using waste	Amount after using tile waste (Rs)	Amount after using Form (Rs)
Total cost to manufacture 1000 pieces of plates	583,022.19	459,840.95	404,660.04
Total cost to manufacture 500 pieces of Hexagon	887,953.34	804,348.36	707,826.56
Additional common costs for both plates & hexagon (in manufacturing)	42,200.00	42,200.00	42,200.00
Additional equipment to setup these	192,600.00	192,600.00	150,000.00
Transportation of tile waste from factory to site	0	25,827.19	25,827.19
Summary of proposed project manufacturing	1,705,775.53	1,524,816.50	1,330,513.78
Saving from the tile waste than normal concrete		180,959.03	
Saving from tile waste and form concrete than normal concrete			375,261.75

This method not only optimizes costs but also maximizes the covered sea area to 402.4m², making it the most efficient and economical solution. It's important to note that further research is necessary for a more comprehensive exploration of cost minimization and analysis, but such investigation lies beyond the scope of this current research.

Furthermore, this approach contributes to the effective utilization of ceramic tile waste, typically disposed of in the environment, leading to environmental damage. By incorporating this waste material into the construction process, the project not only minimizes disposal-related environmental harm but actively transforms a potential pollutant into a valuable resource. Therefore, the overall benefit derived from this initiative is exceptionally high.

3.8 Chapter Summary

This chapter explores the development of materials and structures, emphasizing sustainable practices to ensure compatibility with marine ecosystems and minimize harm to coral reefs. (XRD) analysis was pivotal in identifying the crystalline structure and composition of ceramic tile waste sourced from three companies in Sri Lanka. Waste samples from dry squaring, wet squaring, and glazing processes were analyzed, revealing key minerals such as quartz, nontronite, and albite. The sieve analysis confirmed the potential of ceramic waste as a fine aggregate in concrete, with Samples 1 and 2 exhibiting patterns similar to sand. A series of concrete mixes (M1 to M5) were designed, replacing fine aggregates with varying percentages of ceramic waste. Mix M1, incorporating 25% ceramic waste, demonstrated the best workability and achieved the highest compressive strength (49.9 MPa) at a 0.5 water-to-cement ratio. Slump tests highlighted the need for increased water content with higher ceramic waste proportions, while cube tests confirmed the superior strength of ceramic waste-enhanced concrete compared to traditional mixes. These findings informed the fabrication of concrete modular units, which were deployed in a marine environment for future performance evaluation, underscoring the potential of ceramic waste as a sustainable and effective material in construction applications.

Enhancing the porosity of concrete modular units was identified as key to promoting coral growth by improving water circulation and enabling the exchange of nutrients and gases. Foam concrete (FC), a lightweight, cellular material with high porosity, was explored for this purpose. Produced by mixing cement, sand, water, and foam with performance-enhancing additives, FC reduces weight and cost while maintaining essential structural properties. In this study, a mix using 25% ceramic tile waste as fine aggregate replacement achieved optimal compressive strength of 49.9 MPa. Varying foam percentages revealed that a 26 % foam mix reduced weight by 10% (from 75.68 kg to 66.5 kg) and met the strength requirement of 25 MPa, making it suitable for modular applications. While 26% foam achieved further weight and cost reductions, its reduced strength rendered it less practical. Foam percentages beyond 30% were unsuitable due to critical strength loss. Thus, the 26% foam mix provided an ideal balance of porosity, strength, weight reduction, and cost-efficiency for sustainable coral modular design.

4 DEVELOPMENT OF THE STRUCTURES AND SAMPLE DEPLOYMENT

4.1 Development of the concrete modular

This section shows the inspiration, how that inspiration modeled, how the prototypes created using materials etc. Inspiration for the design of the modular is taken directly from the coral itself the following image Figure 4.1 illustrates it. The bonding or the interlocking look-like structure is used as the inspiration for the modular. The modular, known as the marine hub, is inspired by the corals rather than the modular named Coral Hab.

The initial design was inspired by the mechanism of the puzzle. The reason not to use this is the layout should be laid on flat surfaces. But under the sea, the ground is not perfectly leveled to lay puzzle-type structures. The design should be developed to be fixed and should be able to lay on non-flat surfaces. These structures should also be stable under pressure.

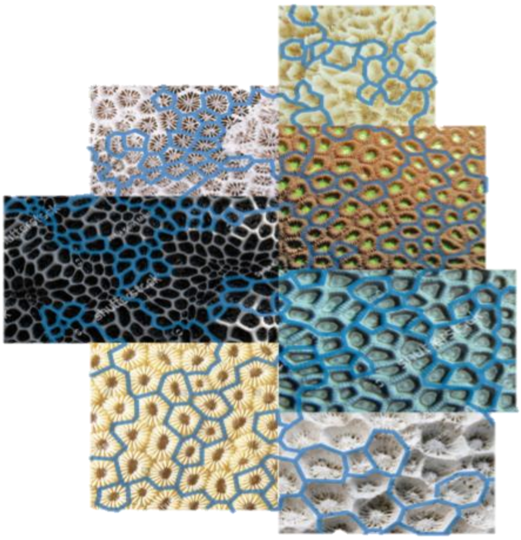

Figure4.1 :Colorful Coral structures

After brainstorming a set of sketches was drawn to figure out the most appropriate design that can be used to create the best concrete modular to plant corals and make a habitat for marine life. When drawing sketches, the main concerns were the walking path that can be created by the structures and what will happen to the concrete blocks, will it be comfortable, will they be environmentally friendly.

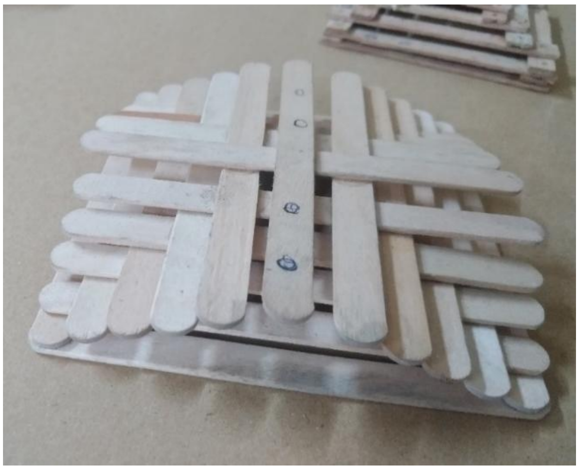

Figure 4.2: Coral Hab system made of wood

A set of sketches was selected to go through the next step, which is the development of physical models Figure 4.2. These physical models were created using hardboards or wood. The behavior of the physical model, and how it operates will be thoroughly observed during this step. This concept is implemented by the inspiration of Lego module systems. Created physical models are shown in the below figures 4.3.

Figure 4.3: Structure made of hardboard.

The hardboard model below shows how the structures are interlocked, and the interlocking shape was changed several times. The top interlocking structure has a circular shape then it got changed to a triangle shape. Also, under the sea due to the movements and bumpy surface, these interlocks can break so there are small spacing's in the interlocks so that they won't fit perfectly to the other parts it will have small paces to bear the sea movements and bumpy surfaces like Figure 4.4.

Figure 4.4: Hardboard model of marine condo

4.2 3D Modeling

Figure 4.5: 3D modeling of Coral Hab:

After a thorough observation of the physical model 3D modeling is done using Sketch up, and Lumion Figure 4.5 and Figure 4.6. The first two figures shows the first structure in which the coral is planted. Coral growth can be visible in the holes and on the surface of the first two figures down below. The next structure is used for the walking path and is like interlock paving blocks. The holes in the blocks will create a safe habitat for marine life and corals. The walking path will not harm the marine life underneath.

Figure 4.6: 3D modeling of Marine Condo

4.3 Design Development

Design development consists of the two structures how they are made, what are the special characteristics of each structure and how these structures contribute to protecting marine ecosystems.

4.3.1 Coral Hab

While some structures lie freely on the substrate underneath or next to infrastructure, others are made to be linked to it. These components, or variations, might be included in the planning of brand-new infrastructure or added to already-built buildings. Most of the "independent" components might be adjusted to hang from underwater infrastructure.

The specialty of this structure is that most of the structures created regarding this study are structures that are built in labs and deployed to the sea requiring lots of manpower or huge ships or containers or machinery. Most of the designs did not even comply with the study environment.

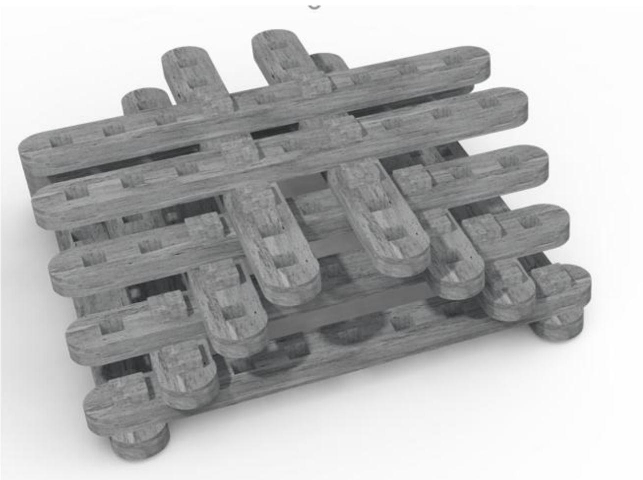

Figure 4.7: Coral Hab system

The figure below is the single unit that can create various structures. To develop various structures the interlocking nut is used to connect each Hab. The researcher has created structures like pyramids using this single Coral Hab Figure 4.7. To build a reef, without putting stones, these units can

- blend with the reef
- support the dying or broken reef

This structure pretty much acts as a skeleton. The skin that will be added to the skeleton will be coral. So, the unit is very much attached to the corals. When deploying one person can lift two units as these structures are very light in weight. Most of the past literature structures are fixed using metal nuts and those nuts can be corroded within a short period and pollute the sea. The nuts used in this structure are also concrete.
A technical drawing of the Coral Hab is shown below in Figure 4.8 and Figure 4.9

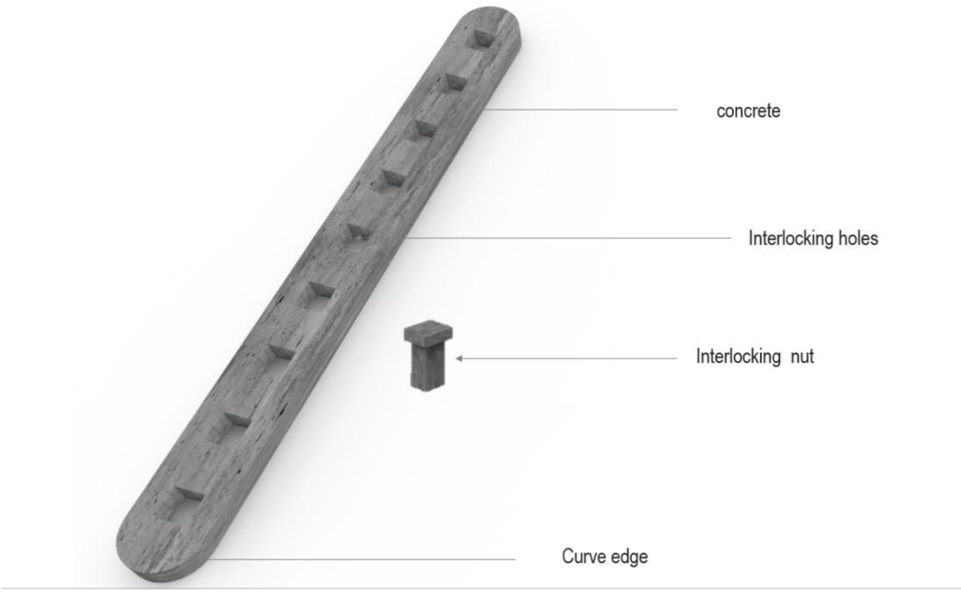

Figure 4.8: Components of the Coral Hab

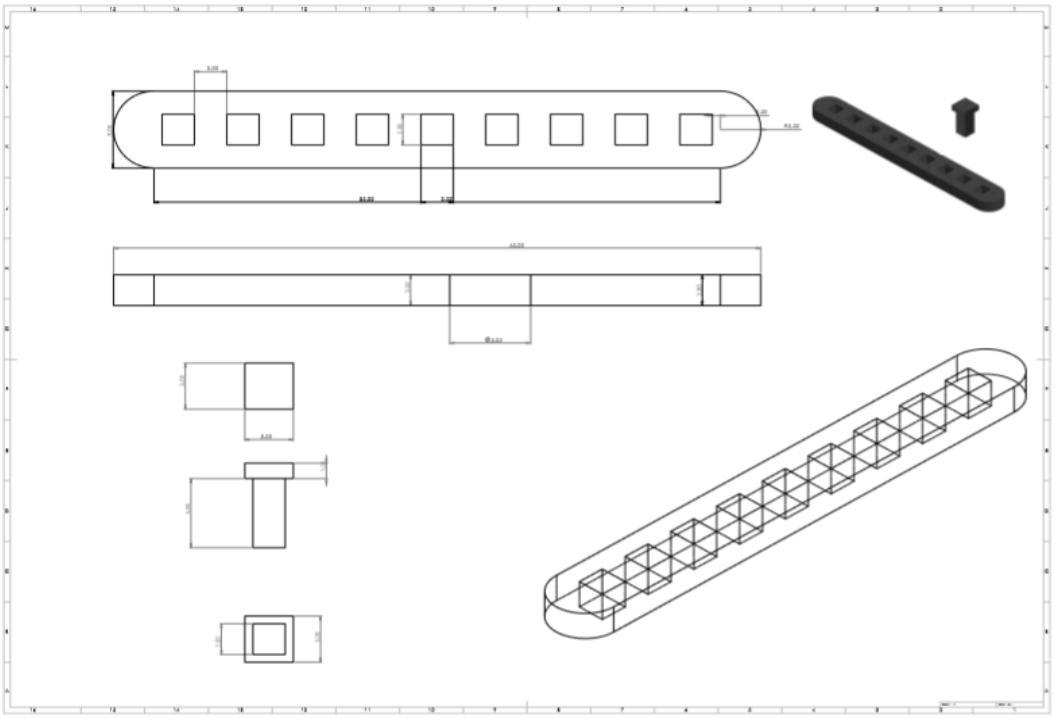

Figure 4.9: Technical Drawing

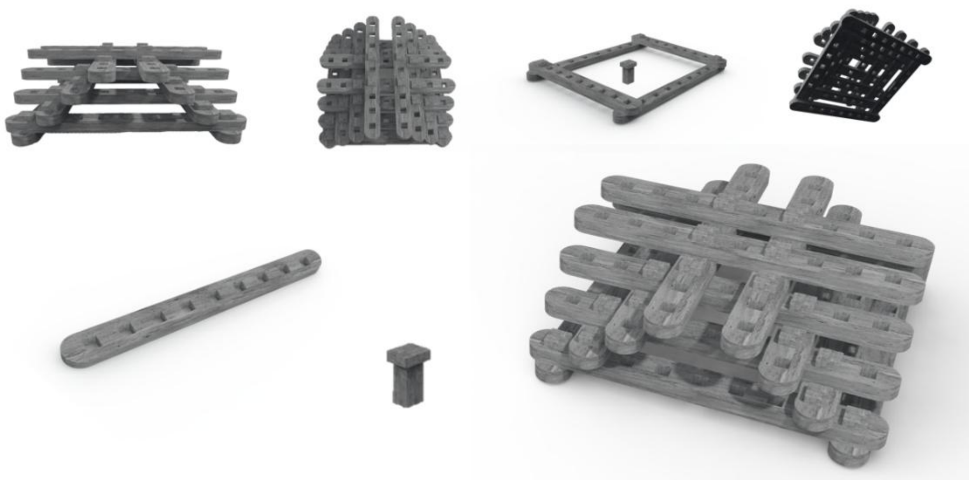

Figure 4.10: Coral Hab structure creating process

The below figures 4.10 below show the actual structure made using concrete. Coral attachment to the surface will be low on a smooth surface. The rough surface has a higher attachment ability than smooth surfaces.

Figure 4.11: Curve Edge

The below figure 4.11 clearly shows the holes and the nut is made in a rectangular shape because when in circular shapes the structure can be easily removed from the nut Figure 4.12. Also, the below figures indicate there are lots of rectangular holes in a single unit. Some of the holes will be used to connect with nuts and the rest of the holes can be used as coral planting pots it explained in Figure 4.13 and Figure 4.14.

Figure 4.12: Interlocking System

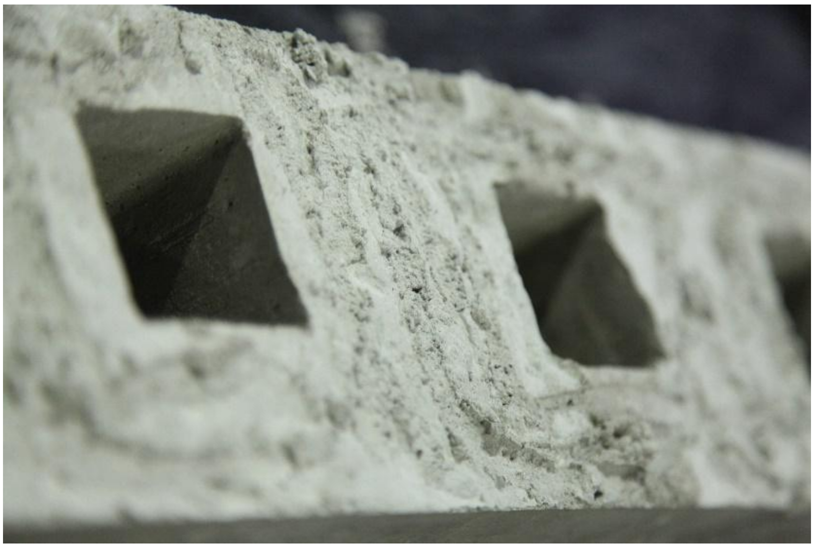

Figure 4.13: Rough Surface

Figure 4.14: Hole for connect modules.

4.3.2 Marine Condo

To contribute to their stability in higher energy conditions, modules might potentially be fastened to the substrate as well as linked to the infrastructure. It is crucial to consider a module's structural stability in tidal areas, as well as under storm and flood conditions. This unit is mainly used for underwater paving. This acts as a safe walking path for people as well as provides a good habitat for marine life. This can also act as a breakwater system. If the structure is placed upside down, it can also be used as a pot to place mangrove plants. Refer to Figure 4.15 to Figure 4.19 for a visual representation

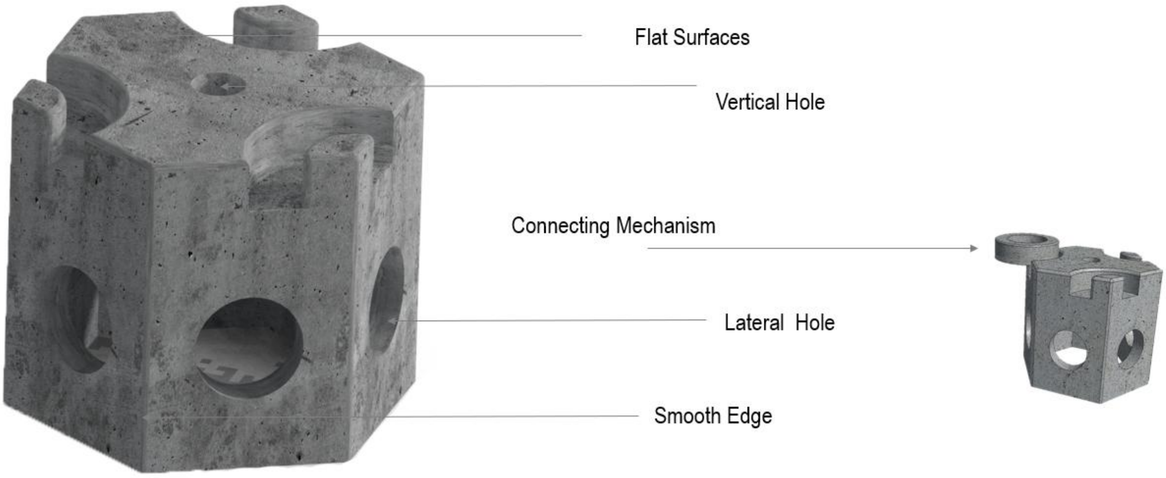

Figure 4.15: Parts of Marine Condo

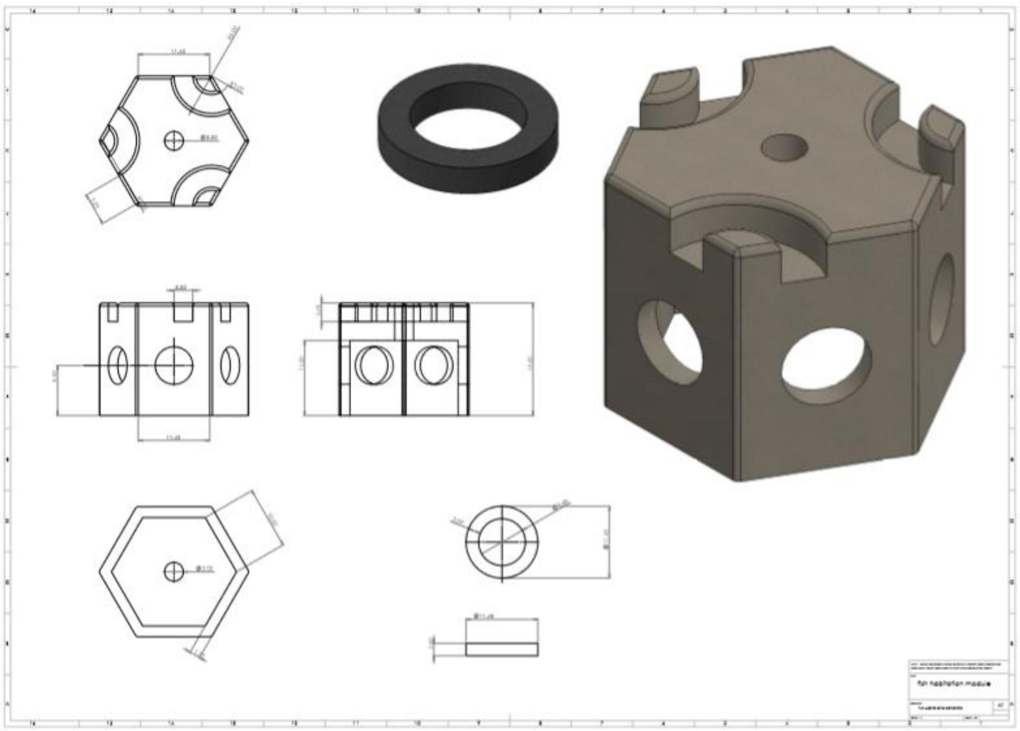

Figure 4.16: Drawing of Marine Condo

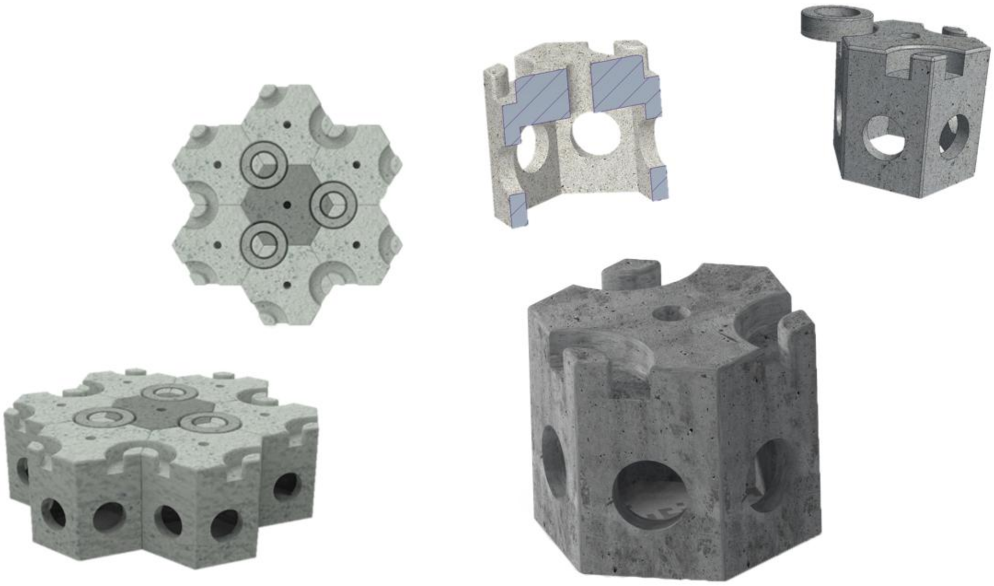

Figure 4.17: Detailing of the Marine Condo

Figure 4.18: Smooth edges with a rough surface

Figure 4.19: Lateral Hole / Vertical Hole

4.4 Deployment Area

Deployment areas are in Polhena, Matara, and Sri Lanka. Polhena is a well-known fringing coral reef and reef lagoon located within 2 km from Matara city having high economic and ecological importance while heavily exploited by the holidaymakers and fishermen on the other hand (Figure 4.20). Many local and foreign visitors visit Polhena because the area is blessed with immaculate stretches of coral reef, enriched with high biodiversity. Over the past de Cades, the fringing reef cover of Polhena is being damaged by many tourists without any control.

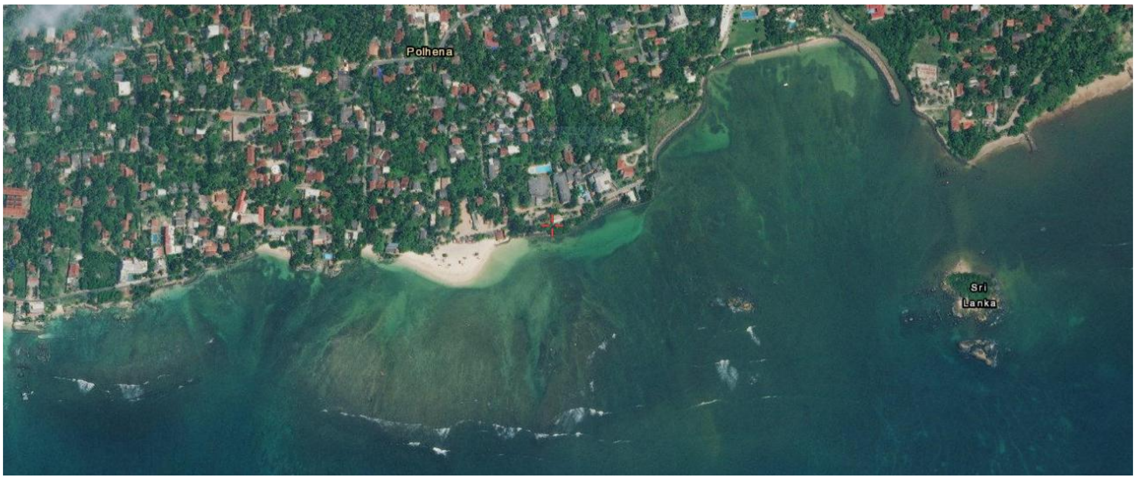

Figure 4.20: Project Area

Source: google map

Polhena is a well-known fringing coral reef and reef lagoon located within 2 km from Matara city having high economic and ecological importance while heavily exploited by the holidaymakers and fishermen on the other hand. Many local and foreign visitors visit Polhena because the area is blessed with immaculate stretches of coral reef, enriched with high biodiversity. Over the past decades, the fringing reef cover of Polhena is being damaged by many tourists without any control.

The best time to grow corals is known to be from June to September (national science foundation, California) ideal time to let the corals have their own time to regrow from the damage done with the tourism season the temperature is higher compared to the other times of the year. The oceans around Sri Lanka are "micro-tidal," which means that there is less than a meter of variation between high and low tide. Every day there are two high tides and two low tides, with their timing and size determined by the position of the sun and moon, deep ocean tidal patterns, the shoreline's form, and the depth and topography of the nearby sea floor. (Perera & de Vos, 2007)

<u>Recorded other fish species in the Polhena Sea</u>

- Spur Check Cardinal fish- Apogon fraenatus
- Longfin Bannerfisgh - Heniochus acuminatus
- Semicircular angel fish - Pomacanthus semicirculates
- Dusky Wrasse - Helichoeres marginatus
- Pomacanthus imperator
- Neopomacanthus azyston
- Pterios antennata
- Valenciennes - Labroides dimidiatus
- Pomacanthus similis

Polhena Beach attracts a diverse range of users, categorized into foreign, foreign/local, and local groups. Foreign tourists primarily visit for holidays, usually as couples or families, staying in hotels and contributing significantly to the local economy, though their interaction with locals is limited. In contrast, backpackers**,** a growing trend in tourism, seek authentic, budget-friendly experiences by staying in homestays or hostels, contributing minimally to the economy. The foreign/local group includes marine biologists, who are drawn to the area's biodiversity. Among local users**,** residents capitalize on tourism by setting up small businesses during peak seasons, while local youth enjoy snorkeling and the area's appeal as a spot for young couples. Non-resident locals, who visit mostly for recreation, often leave litter behind, especially after consuming alcohol, and frequent the beach during weekends and holidays, enjoying its access to live coral and turtle-watching areas.

Figure 4.21: Description of the Project area

4.5 Deployment of Coral Hab and Marine Condo

Deployed the samples in shallow water. Machinery and equipment were not needed to deploy the sample as these were lightweight, especially the Coral Hab. The marine condo was taken to the area by placing it in a tube. Samples can be deployed at any time and at any number unlike other structures needed to be placed at once with several samples to study. Refer to Figure 4.22 to Figure 4.29 for a visual representation of these module workability

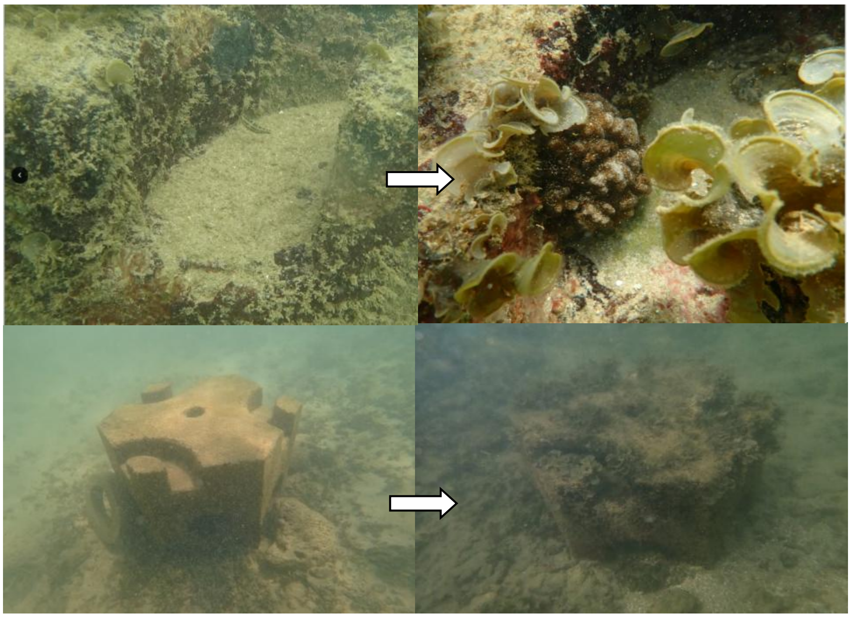

Figure 4.22: Marine Condo 6 months and 1 and a half years after deployment

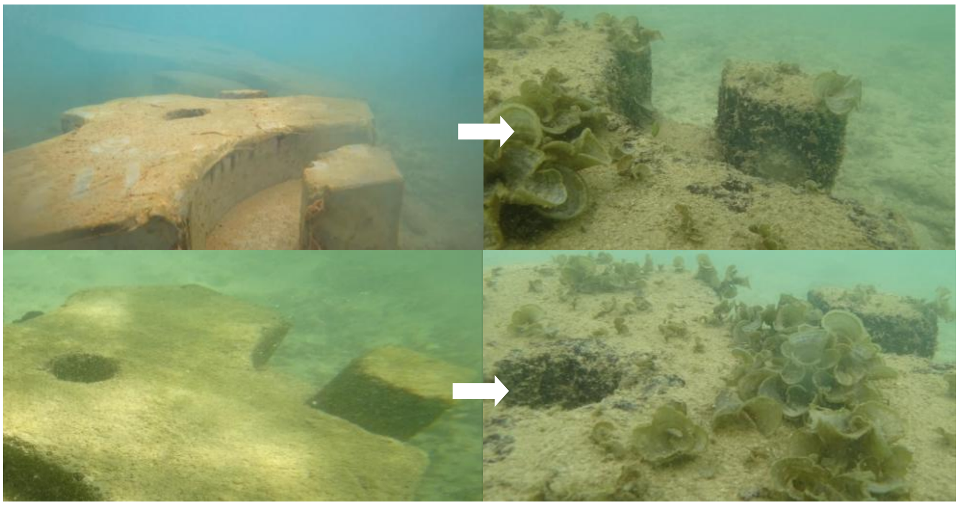

Figure 4.23: Marine Condo just after and 6 months after deployment

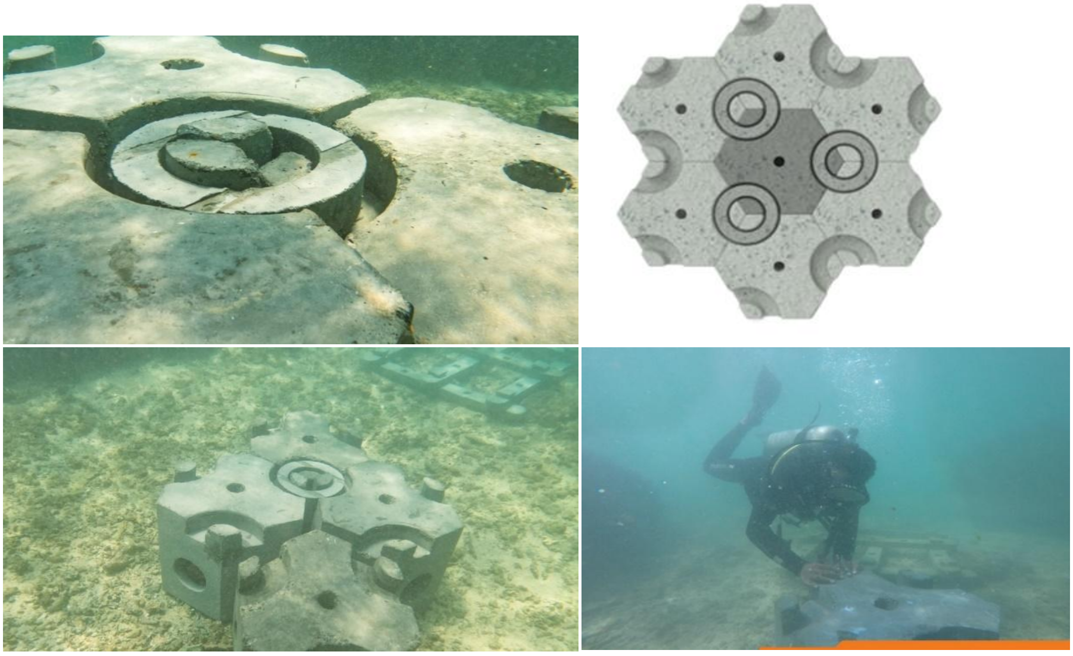

Figure 4.24: Connecting Marine Condo modules and deployment.

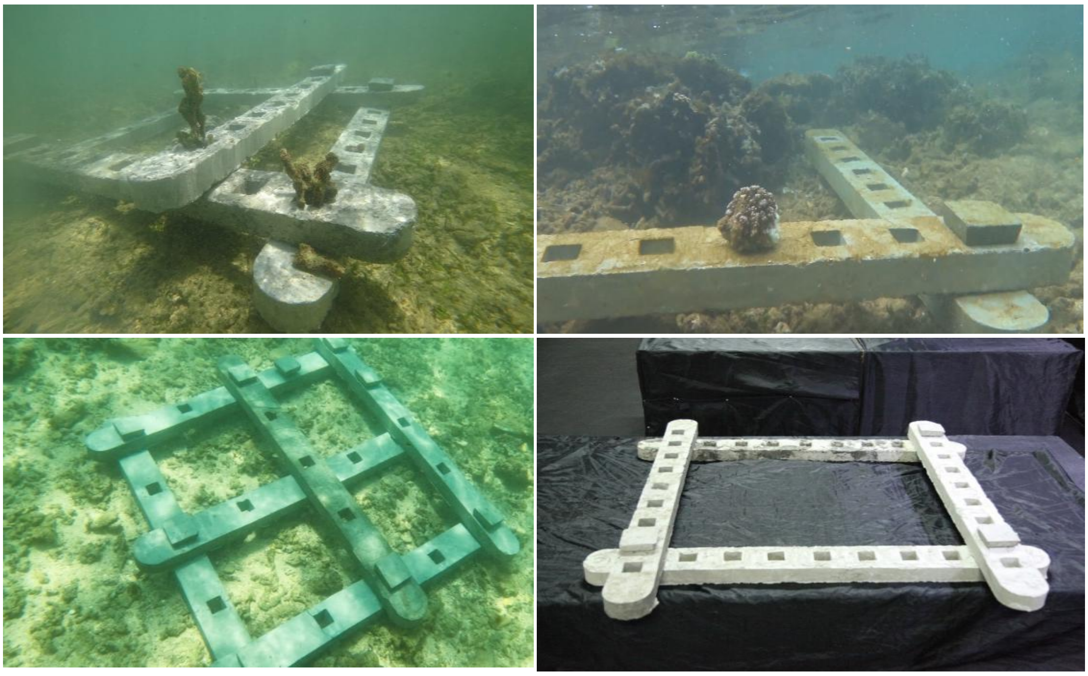

Figure 4.25: Connecting coral Hab modules and deployment

Figure 4.26: Coral Hab before (a) and 18 months (b) after deployment

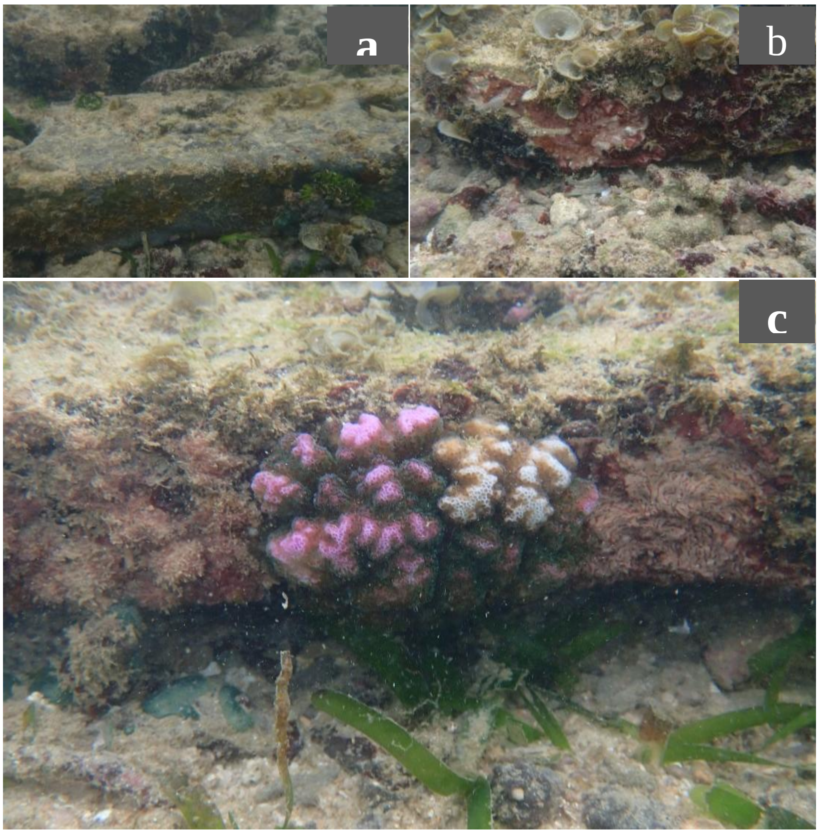

Figure 4.27: Growth of coral in the structures after 6 month (a), 12 month (b) and 18 months (c)

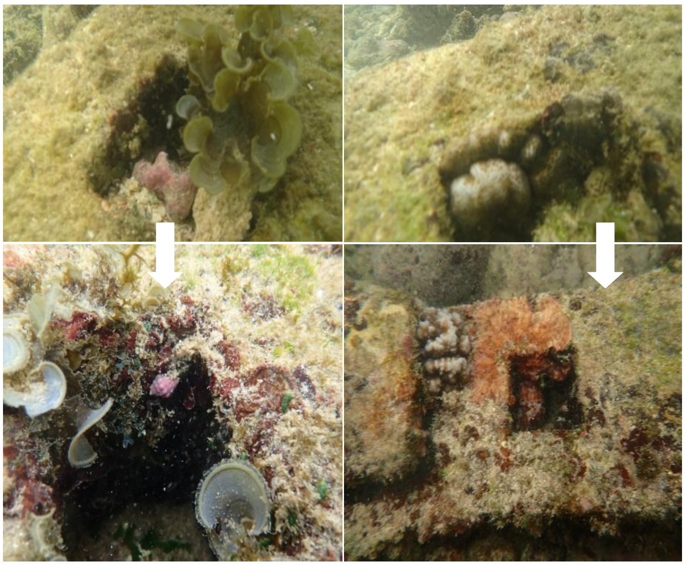

Figure 4.28: Growth of colorful corals on top of the structures

Figure 4.29: Coral Hab before (a), after 6 months(b) and after 18month(c) deployment with the growth of corals

4.6 Selected Coral for plantation

These three varieties are the primary coral species found in Sri Lanka's southern region. After Acropora tenuis, Acropora millepora is arguably the most well-known species of Acropora. This SPS coral's popularity waxes and wanes, yet it is consistently an extremely sought-after coral.

Simple observation explains why this specific Acro is so unique to us: whenever you snorkel on a shallow, quiet reef, you can easily find them. They just sparkle above the reef, drawing our attention to them like a magnet. There is no other coral in the world that can compare to its colorful vivid hue and fluffy look brought on by its long-extended polyps. They inhabit calm, murky, shallow reefs that virtually protrude out of the sea during low tide. Their coloring is unmatched, with frequent bicolor tips that contrast with the color of the colony with an orange axial coralline. Due to the absence of golden-brown zooxanthellae, the colony's tips are often darker than the rest of it, while the colony's core is vibrantly colored and has long tentacles of contrasting colors that give it a fluffy look.

Tentacles are often green, white, and occasionally crimson. The colony's hues run the gamut from light pink to purple and scarlet to lime yellow to lime green to vivid orange and gold. Acropora millepora is the only species of coral with such a wide range of hues. The below figure shows a picture of Puff fish. Most of the coral in Polhena has been destroyed due to human activities and it has destroyed the homes of the sea creatures like this. The first picture and the second picture's time difference are one and a half years. The first picture was taken two days after the sample deployment the following image Figure 4.30 illustrates it. So, this Puff fish has taken this paving block to be his home for a very long period.

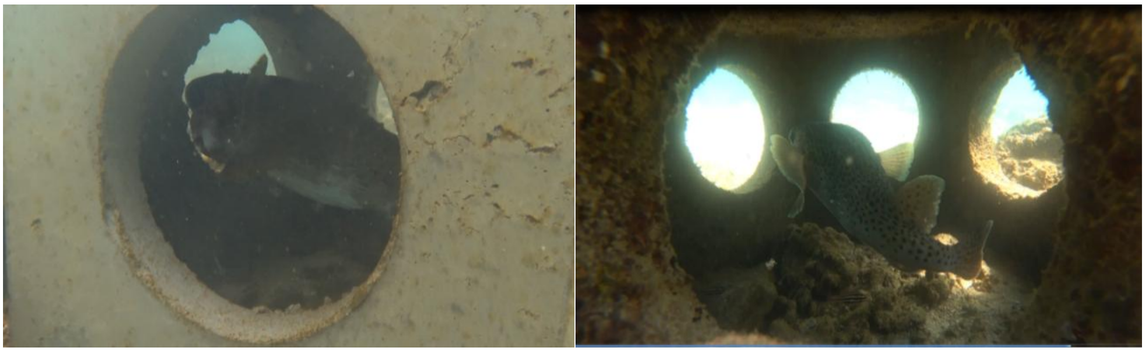

Figure 4.30: Fish choosing Marine Condo as its habitat

4.7 Chapter Summary

This chapter provides an in-depth exploration of the design, creation, and deployment of the Coral Hab and Marine Condo structures, focusing on the development of various 3D models and key design features aimed at promoting coral growth. It highlights the characteristics of these structures, particularly the special features designed to foster a healthy marine ecosystem by attracting and supporting coral colonies. A significant portion of the chapter is dedicated to the deployment process, where the effects on surrounding habitats and marine life are closely examined. The selection of the deployment area is also carefully discussed, with emphasis on the unique advantages of the chosen location over alternative sites. Special attention is given to the types of corals selected for plantation, offering a deeper understanding of the broader marine ecosystem's dynamics.

Additionally, the chapter delves into an innovative approach to concrete composition, with the use of foam concrete as a means to enhance the porosity of the materials. This modification supports coral growth by improving water circulation, nutrient exchange, and the attachment of coral larvae. The use of foam concrete was tested experimentally, utilizing a chemical foaming method with a detergent-based foaming agent to create a cellular, lightweight material with improved structural characteristics. This exploration reveals how the modified concrete can reduce weight, leading to material and transportation cost savings, while also offering enhanced sustainability.

The chapter further explores the significant benefits of incorporating foam concrete in the production process, including its ability to reduce the overall weight of the concrete modules, thus lowering material and transportation expenses. The use of ceramic tile waste as a substitute for fine aggregate has also been investigated, showing how it can boost the compressive strength of the concrete while maintaining an eco-friendly profile. The Polhena area, strategically chosen for its favourable environmental conditions, emerges as a key location for coral regeneration, benefiting both marine life and the local community. The results underscore the positive impact of the project, extending beyond ecological benefits to support the well-being of nearby residents.

5 CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

- The first chapter fulfills the first two objectives of the study which are an investigation of the ceramic glazed tile waste produce, applications within the availability and ability to use wastage of ceramic glazed tiles in the Sri Lankan context, and the research of the marine biological and marine geological environment in Sri Lankan coastal area. In the marine biological context, the types of ecosystems, differences of ecosystems, characteristics of each ecosystem, marine ecosystems, coral reefs as eco systems their structure, and threats to these coral reefs have been discussed. After that development of coral structures using different materials is discussed.

- Then discussed different waste material types that can be useful to develop suitable concrete and then finally selected wastage of tiles that are ceramic glazed to produce the concrete. The next part of the literature review is focused on the ceramic material types, ceramic tile production, and the characteristics of ceramic tiles are discussed. So, the main two goals of the study are completed within this chapter.

- Structure development represents all the inspirations and 3D models used to develop the two final structures named Coral Hab and Marine Condo. This part thoroughly discusses the nature of these two structures and the special features used to attract corals. The final chapter discusses the deployment of the two structures and how the habitats changed around the structures, how the marine life revolved around the structures, why the selected area is more suitable other than any other area, and the information on the coral types that were proposed to plant. Deploying procedure is thoroughly discussed in the chapter. In this chapter, I found out that the selected Polhena area had many advantages in reforming corals not just for the marine life but also for the people.

- The Forth chapter fulfills the study's third objective, which is to develop the best mix and structural arrangement to maximize strength and check the cost-effectiveness of the Marine Concrete Modular. The first part of the chapter shows the study's material development, and the next represents its stricture development. In material development, the development of the mix design with the correct ceramic waste proportions is discussed using tests such as the XRD test and sieve analysis. From the XRD test, the perfect ceramic waste out of 4 samples is selected (which is sample 2). Using sample 4 the mix design was developed, and this design was checked with a slump test and cube test to check the strength and workability parameters.

5.2 Recommendations

- In Sri Lanka, waste products from ceramic tile plants include sludge, glaze, and ceramic powder, none of which can be dealt with locally. Every firm has tried to offer a better solution, but now there is a need for a standard way to get rid of this waste. This is crucial not just for giants in the ceramic manufacturing industry like Europe, India, and China, but also for Sri Lanka, an island with few manufacturers. Over time, this will become a serious issue since ceramic waste will decompose for a very long time without being contributed to the environment. In this investigation, tile fragments weren't considered. The primary emphasis has been on polishing and reducing waste.

- It should be less expensive to reuse ceramic waste than to dispose of it to create the illusion of interest. After the process of recreating, tile fragments are frequently employed. But because tile-squaring is powdery, it may be utilized to produce other goods profitably. Even though there are sophisticated waste management systems available, Sri Lanka does not effectively employ them.

  Trash may be reduced by recycling as much waste as possible without sacrificing the tile's quality, and by using various types of wastage in another appropriate sector, can make the best use possible of our environmental resources while also protecting the environment. It can be demonstrated by XRD testing that it contains no materials that are detrimental to the environment or living things. This ceramic powder's strength, heat resistance, and other qualities make it perfect for manufacturing crucial goods.

- These are utilized in the mixing of concrete, according to several additional study references. Additionally, dry squaring only removes a little quantity of waste. Small ceramic goods made using ceramic casting can be made using these. For the construction of roads, it can also be used with tar and concrete.

  Tile fragments may also be used for this, however, following the disintegration of the tile and cement, the tiles that have very sharp edges might damage the cars moving on pavements.

- This waste from ceramic manufacturing might potentially fill a sizable area. Also, field research is being done to use this waste for the development of marine species in preparation for future tests. We saw that several kinds of algae started to form on it in just two months.

  With the right methods and fresh tests, the waste of the ceramic polishing and squaring which is burnt ceramic dust has a big use to be in the manufacturing procedure and reduces environmental harm. For projects aimed at protecting the environment, garbage can be recycled.

5.3 Future works

- Explore Alternative Applications: Investigate additional uses for ceramic waste, such as blending it with materials for construction or infrastructure (e.g., asphalt, bricks, and eco-blocks).

- Study the possibility of developing composite materials using ceramic waste for applications in lightweight construction, thermal insulation, or fire-resistant panels.

- Marine Applications: Expand research on using ceramic waste to create artificial marine habitats. Test different structural designs and materials to assess their impact on marine biodiversity and coral growth over time.

- Conduct long-term studies on the environmental impact of ceramic waste decomposition and potential leaching effects on marine and terrestrial ecosystems.

- Develop Standards for Waste Utilization: Establish guidelines and standardized methods for ceramic waste management, recycling, and reuse in Sri Lanka.

- Conduct economic analyses to compare the cost of ceramic waste disposal versus its reuse in various applications.

- Perform LCAs to measure the environmental footprint of products made with ceramic waste.

- Launch awareness programs to educate local communities and industries on the benefits of ceramic waste recycling and Work with policymakers to incentivize waste recycling and sustainable practices within the ceramic industry.

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