Abstract. This research aims to develop and understand the impact of seaweed as a bio-based material within architecture and design. The research is influenced by current global challenges, outlined by the Sustainable Development Goals (SDG), such as carbon drawdown, the problem of material waste, and the need to create more sustainable manufacturing processes. Seaweed is an organic biomass that does not require land, fresh water or fertilisers to grow, and growing it can reduce the effects of global warming as it sequesters large amounts of carbon dioxide. In turn, it can be harvested and used for a range of products including food, biofuel, fertiliser and bioplastic. The research focuses on the development of an organic, water-based biocomposite material made from sodium alginate, a derivative of brown seaweed, combined with cellulose powder, vegetable glycerine, and kelp powder. A set of methodical experiments were conducted and studied, with the aim of creating a novel material which can adapt to its surrounding environment and can degrade naturally. By creating and fabricating using renewable resources, one can create novel materials that are carbon neutral and contribute to a natural resource cycle. Ultimately, the material decays and returns to the earth, for the purpose of remediating soils and replenishing growth.

Keywords. Seaweed Biocomposite Material; Paste Extrusion Method; Water-based Robotic Fabrication; Circular Design; SDG 12; SDG 13; SDG 14.

1. Introduction

The global challenges we are facing due to climate change and the depletion of natural resources is forcing us to radically change the way we design and construct our built environment by taking a new critical stance on the materials we use and the resource cycles that we create. The construction industry plays an important role in all industrial sectors, as it currently is responsible for a substantial share of resource consumption, energy use, carbon dioxide emissions and waste generation (Bekkering et al., 2021). This is having a catastrophic effect on our surrounding environment which can be seen within our natural ecosystems. With growing concerns about the effects of global warming on the environment, there needs to be a shift in the way we interact with our natural environment by integrating nature-based solutions into all sectors of our daily
lives, especially in architecture and design.

The research is framed within the same aspects as the UN’s Sustainable Development Goals (SDG) or Global Goals which are a collection of interlinked goals designed to be the starting point in achieving a more sustainable world for future generations. The SDGs were set up in 2015 by the United Nations General Assembly and are aimed to be achieved by 2030. This research focuses on three interrelated goals of the SDGs, namely goals: (12) Responsible Consumption and Production: to ensure sustainable consumption and production patterns, (13) Climate Action: to take urgent action to combat climate change and its impacts, and (14) Life Below Water: to conserve and sustainably use the oceans, seas and marine resources (United Nations, 2015). The challenge is to reduce non-renewable resource consumption by turning to renewable resources that alleviate the effects of climate change in their production instead of contributing to it. The research focuses on tackling these goals by looking to the ocean and its resources for alternative solutions. Coastal ecosystems are some of the most productive ecosystems on Earth and are made up of biomass such as seagrass meadows, mangrove forests, salt marshes and kelp forests. These ecosystems are collectively known as Blue Carbon ecosystems as they account for large amounts of carbon sequestration from the ocean and atmosphere, acting as carbon sinks.

2. Blue Carbon Strategies

The oceans itself accumulates vast amounts of carbon within coastal ecosystems, known as Blue Carbon. These ecosystems occur in shallow waters and account for 50% of long-term carbon sequestration, while only making up 2% of the ocean (IUCN, 2021). These coastal systems, though smaller in size compared to terrestrial forests, sequester carbon at a much faster rate. They provide numerous other benefits such as shoreline protection from storms, rising sea levels and erosion, regulation of coastal water quality, provision of habitat for marine life, as well as food security for many coastal communities (The Blue Carbon Initiative, 2021). Despite their importance, Blue Carbon ecosystems are largely under threat from climate change, fishing, pollution, marine pests, and coastal urban development (Duarte, 2021). Therefore, coastal habitat conservation is a good strategy to implement in order to reduce the effects of climate change on these important coastal ecosystems.

2.1. KELP FORESTS

The research considers the production, harvesting, and use of seaweed as a Blue Carbon strategy, and how this material can be harvested sustainably as a building material. Seaweed is a term that can be used to describe many different species of macroscopic, multicellular marine-based plants and algae. Seaweed grows in a variety of forms and colours in the ocean as well as in freshwater environments. There are thousands of species of seaweed, with kelp being the largest subgroup of seaweed. Seaweed can be broken down into three main categories based on pigmentation: Rhodophyta (red), Chlorophyta (green) and Phaeophyta (brown). Kelp is placed in the Phaeophyta (brown) category and includes the largest and fastest growing seaweeds, such as macrocystis pyrifera, more commonly known as giant kelp. On average, giant kelp grows at a rate of 28cm a day but can grow up to 60cm a day in ideal conditions,
making it one of the fastest growing plants on the planet (NOAA, 2021). Kelp grows in dense groupings that form ocean forests that harbour a greater variety and higher diversity of marine plants and animals than almost any other ocean community, making it one of the most productive and dynamic ecosystems on Earth.

2.2. REGENERATIVE OCEAN FARMING

Aquaculture or regenerative ocean farming is a farming practice that is found in the ocean and incorporates the growing of seaweed and other marine life such as oysters, mussels and scallops. These farms are cultivating and harvesting seaweed, which is becoming a competitive biomass production candidate for food and related uses. There are several organisations such as AtSeaNova and GreenWave that are developing systems that focus on regenerative seaweed farming. GreenWave has come up with a 3D vertical ocean farming system which consists of underwater vertical gardens that grow kelp and shellfish on suspended floating ropes. This vision aims to combat the effects of climate change as well as create jobs in local communities and rebuild marine ecosystems. The National Oceanic and Atmospheric Administration (NOAA) is investigating this industry’s benefits, as it is still in a developmental stage, which will lead to more efficient permitting and allow seaweed farming to expand while being economically and environmentally sustainable (NOAA, 2021).

3. Seaweed Material Research

As a natural biomass, seaweed is not only beneficial to the environment as it grows but is also rich in various nutrients that are beneficial to other organisms such as plants and animals. Seaweed is made up of organic compounds such as proteins, amino acids, lipids, cellulose and vitamins, and is also rich in alginate and polysaccharides that are not always present in terrestrial plants. This is one of the many reasons that this versatile macroalgae is harvested and used in both its raw and extracted form for a range of products including food, biofuel, pharmaceuticals, cosmetics, bioplastics, fertilisers and livestock feed. Seaweed extractions such as agar, alginate and carrageenan are widely used in the food industry for their gelling, water-retention, emulsifying and thickening properties (Martău et al., 2019).

3.1. SEAWEED EXTRACTION: SODIUM ALGINATE

Above is Hydrocolloids are defined as a long chain of hydrophilic polymers that are characterised by their capability to form viscous dispersions and/or gels when dissolved in water (Khalil, et al., 2018). Sodium alginate is a naturally occurring biopolymer, extracted from the cell walls of brown seaweeds, which has been extensively investigated and used for many biomedical applications such as tissue engineering and drug delivery, due to its biocompatibility, low-toxicity, relatively low cost and mild gelation by addition of ions such as calcium. The use of alginates is based on two main properties. The first is their ability to thicken in the presence of water and the second is their ability to form gels due to cross-linking of ions in the presence of calcium (Lee and Mooney, 2012). Gels formed from alginates can withstand heat and temperature of up to 150 degrees Celsius without melting, giving it water-resistant and durable properties that can be used within design and architecture.
The aim of the research was to develop a novel, bio-based material using an extraction of brown seaweed as the core biopolymer, which would be combined with additional materials to create a stable and extrudable composite. Bioplastic composites are created by combining biopolymers for strength, plasticisers for flexibility, additives for additional properties such as texture, colour, strength and durability, and a solvent such as water. This is made by cooking the materials using a heat source to create a homogeneous solution that can be cast into a die and dried using a heat source (to speed up the curing time and to prevent the material from molding). The materials chosen to start the experiments were water as the solvent, sodium alginate powder as the biopolymer, vegetable glycerine as the plasticiser and kelp powder as an additive. Based on bioplastic material research, other natural materials such as sunflower oil (which shows promising results in reducing the shrinkage), cornstarch combined with vinegar, chitosan, hemp fibre and calcium chloride solution (used to create a gel layer by cross-linking of sodium and calcium ions) were added methodically to gain an understanding of each material’s characteristics and qualities.

3.2. INITIAL MATERIAL STUDIES

A set of methodical experiments were conducted with different combinations of materials, based on the starting composition of 100ml of water, 2ml of vegetable glycerine, 2g of kelp powder and 5g of sodium alginate powder. A cooking process was used to make the material where water was measured and heated while the sodium alginate powder and kelp powder was slowly added and whisked until a homogenous solution was formed. The vegetable glycerine was mixed in and the mixture was heated while continuously being mixed until it reached a temperature of 90 degrees Celsius before being cast into acrylic frames of 100x100mm and oven dried at 60 degrees Celsius for 2 hours. Because this material is water-based, the time in which they take to cure is an important factor that affects the quality of the outcome. The way in which the material dried and shrunk through evaporation was a key aspect that was considered and was able to be measured against the original acrylic frame dimensions.

After a catalogue of material experiments were tested by adding more of a certain material at a time and measured, it was noted that: the more vegetable glycerine, the more flexible the material became and the less it shrunk (Figure 1A); the addition of spraying a mixture of 10% calcium chloride (10ml calcium chloride in 100ml of water) onto the wet mixture created a gel layer that caused the material to shrink instantly away from the edges of the frame (Figure 1B); and the more sodium alginate added, created a brittle material, which causes the material to tear in multiple places as it dries (Figure 1C). The material experiments were recorded and analysed based on their strength (resistance to tearing), translucency and flexibility during the curing process.

Based on the material experiments carried out, one base recipe was then chosen consisting of a ratio of 100ml water, 6ml vegetable glycerine, 2g kelp powder, 10g sodium alginate and 6g cellulose powder. The addition of another biopolymer (cellulose powder) was added in order to improve the characteristics of the material in which sodium alginate is lacking, such as poor water vapour barrier and mechanical strength. Casting of bioplastics is a common way of exploring base properties of different ingredients and is largely done in bioplastic research, however it is limited in size and control of the material. The viscosity of the wet material was also taken into
consideration as alginate can be robotically extruded. Because of this material quality, additive manufacturing strategies were explored to challenge scalability problems that are often seen within bio-based materials.

4. Additive Manufacturing Strategies

The methodology chosen for fabricating this novel material was to start on a small scale to determine the possibilities and limitations of the material and to then gradually progress to a larger scale. Extrusion printing was chosen to ensure no possibility for material wastage during the additive manufacturing process. A Creality Ender-3 Pro 3D printer with printing dimensions of 220x220x250mm was bought and manually changed to be able to extrude a paste-based solution. This included attaching a 3D printed piece which allows for the attachment of a cartridge containing the material which is then extruded using air pressure. In addition, there is a metal screw attached to a stepper motor placed at the top of the 3D printed piece to assist with the extrusion of the material. It was seen that because the seaweed biocomposite material has a gel-like consistency, it can be extruded using less than 1 pascal of air pressure.

The first experiments looked at extrusion printing three-dimensionally. The alginate biocomposite paste was able to extrude and stick together horizontally and vertically, however the outcome of the material due to shrinkage was not desirable. The printed prototypes shrunk by more than 50%, resulting in brittle elements. An alternative solution was to print two-dimensionally, in order to get results that are characterised by the material properties (Figure 2). Flat sheet printing was chosen and explored, bringing resemblance to the previously explored casting method, but instead of the material being deposited into a die, the material was extruded evenly without scaffolding, giving rise to possibilities within the printing process, including scalability of the material.
The extrusion printing method naturally progressed onto a larger scale by using an ABB140 (IRC5) 6 axis robotic arm where sheets of up to 1000mm could be printed. The novel seaweed material easily adapted to the fabrication process and resulted in one-layered, large, flexible membranes (Figure 3A). During the drying process, the material loses water content due to evaporation. If this happens too quickly, the material has the potential to split in vulnerable areas, however, if the drying process is done within a controlled environment, at room temperature, the material dries evenly across the surface area.

Once there was an understanding that the material was extrudable and dried to form functional membranes, a complexity to the process was added. Multiple layers in the form of vertical and horizontal lines, which were strategically designed to act as structural supports or ribs were added on top of the initial (one-layered) membrane. This gave way for interesting shrinkage patterns and deformations as there was an equal distribution of shrinkage which occurred across the sheet, always towards the centre point of the sheet area. Due to this shrinkage and pulling of the material, the edges of the sheet curl up and away from the surface bed and form evenly distributed sine waves along the length (Figure 3B). In this regard, the material showed resemblance to its original seaweed form found naturally. These unique material behaviours were chosen to be understood and implemented into the design of the material. Instead of working on a way to eliminate them and control the material entirely, the design process emerged from these unforeseen material behaviours.
A catalogue of shapes and strategies were tested all with two to four layers and using a combination of 4-, 6- and 8-millimetre diameter round nozzles. All sheets were recorded and analysed on their size, percentage of shrinkage, as well as effects of translucency, strength and flexibility (Figure 4). It can be seen on average that the sheets shrink 10 to 20 percent in length and 5 to 10 percent in width. Top layer 'ribs' that were designed for structure, and during the drying process started emerging on the underside of the sheets, giving more rigidity. Uniform sine waves appeared along the edges, due to shrinkage and pulling of material between the strategically placed ribs. Uniform gaps and openings started to emerge during the shrinking process where there was not enough overlapping material or weak points in the print.

![Figure 4. Catalogue of Robotically Extruded Multi-layered Sheets](image)

This additive manufacturing process and design was then applied on an even larger scale using a Kuka KR 150 L110-2 Robot. This enabled the membrane to reach a printing length of up to 2000mm, showing that this seaweed biocomposite material can be manufactured on a large scale. There were many factors that affected this large print. Firstly, the 1.4 litre Luthum end effector (used during the printing on the ABB140 robot) was attached to the Kuka, therefore limiting the amount of material that could be deposited at one time. This delayed the completion time, and the top layers and bottom layers were printed separately, which resulted in the layers being disconnected when drying. This affected the overall shrinkage and deformation outcome and produced unexpected results (Figure 5). This research opens possibilities of a novel seaweed biocomposite material that can be additively manufactured on a large scale to produce elements that are natural and biodegradable and can be designed for uses...
within the built environment such as building skins as facade panels.

Figure 5. Large-scale Printing using the Kuka Robot (left) and Dried Results (right)

5. Material Informed Design

In general, water-based bioplastics shrink due to evaporation of water content as they dry and cure. In this case, the loss of water causes the prototypes to shrink evenly towards the geometric centre point, causing spatial deformations. The inverse of shrinkage happens when you expose bioplastic to water. The presence of water or humidity can alter the overall shape of the element because of swelling due to sodium alginate related properties of water-retention. The fact that this research focuses on the recyclability of the elements, being able to dissolve within water is a key aspect that water-based materials have. The elements will need to be studied over time as they adapt to their surrounding environment. In a humid environment they tend to swell and become flexible, however, in a dry environment they stiffen. This research can be further developed to be designed into architectural elements that are durable and degradable and respond symbiotically to its environment so that over time the contents can return to the earth, and as seaweed is a natural fertiliser, it will encourage future growth.

6. Conclusions

The research is driven by current issues of global warming, the problem of material waste, as well as the need to create more sustainable manufacturing processes. The use of seaweed brings attention to underutilised resources that are found naturally in abundance and can be used and produced in a sustainable manner to create alternative renewable materials. Seaweed does not require land, fresh water or any additive fertilisers to grow naturally or farm, therefore, it does not compete with conventional agriculture practises for land space. As a natural polymer, sodium alginate is shown to have many environmental uses and benefits due to its high nutrient and salt content and remarkable mechanical and hydrophilic properties making it biocompatible and biodegradable. Due to its ability to thicken in the presence of water and form gels in the presence of calcium, it can easily be robotically extruded, dried and cured to create a water-resistant membrane which can biodegrade or be broken down and reprinted.

The research is a starting point for further research in this field. The general problem seen today is trying to find a solution to manufacturing these natural materials at a large scale. The use of additive manufacturing of water-based materials, specifically in
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engineering, design and architecture, is still in its early stages and needs to be explored further. Potential future research can be done to improve the extrusion process of multi-material extrusions, material distribution, or other geometric shapes and patterns to suit specific applications. In terms of further material exploration, the addition of chopped fibres or sand particles could be added to the bioplastic recipe and tested to provide enhanced mechanical properties of the printed sheets. Additionally, combining seaweed biocomposite membranes with a substructure of alternate materials such as timber or bamboo can also be investigated in future research.

By approaching the SDGs and tackling topics as large as climate change, the ocean and consumption and production patterns, one needs to find solutions on a small scale that can have a large impact. Seaweed farming has the potential to sequester large amounts of carbon and act as a carbon sink. It can then be harvested and used to create new material systems that encourage the protection and nourishment of the ecosystems from which they come. Replacing non-renewable resources with their bio-polymer alternatives will enable the ability to customise materials to be created, used, recycled and replenished to reduce the effects of climate change while fuelling future growth.

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