Journal of Applied Phycology
https://doi.org/10.1007/s10811-023-03051-7

RESEARCH

Biomasonry products from macroalgae: A design driven approach to developing biomaterials for carbon storage

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Received: 21 March 2023 / Revised: 27 June 2023 / Accepted: 25 July 2023

Abstract
Lowering the embodied carbon of building materials requires a transition away from fossil derived products towards bio-based alternatives, alongside the design and development of new clean tech biomaterials that can function as carbon sinks. This paper presents an overview of historical and existing uses of seaweeds in construction to identify gaps and opportunities for the development of seaweed-based construction materials that can support atmospheric carbon removal through algal photosynthesis. This study highlights the value of interdisciplinary research collaborations that can be situated within the expanding field of biodesign where design research and methods are used to influence the development materials science. It presents as a case study the design of seaweed bricks utilising a biorefinery framework that aims to valorise residual seaweed biomass being grown for waste-water management, identifying value-adding opportunities for this seaweed by-product and new possibilities for carbon storage in the built environment. It details the development of a 1:1 scale prototype for the purposes of an exhibition at the Art Gallery of South Australia in order to demonstrate what biomasonry products from macroalgae can look like, to build social acceptance and to encourage future uptake of sustainable seaweed construction products.

Keywords Seaweed · Sustainable design · Building and construction · Biorefinery · Biomaterials · Carbon sequestration

Introduction

Decarbonising the construction industry: Taking a biorefinery approach

Most building materials continue to be made from non-renewable resources using extractive, exploitative, and energy intensive processes. With the global population projected to reach 9.8 billion by 2050, there is an urgent need to reduce the Green House Gas (GHG) impacts of the construction industry and to develop more sustainable product solutions. Recent studies have investigated the potential to create building products that can sequester atmospheric carbon (CO_2) and act as carbon sinks, a positive and necessary contribution from the sector towards addressing the climate emergency. A 2021 review identified 13 approaches to decarbonising the construction industry using existing carbon storage technologies (Kuittinen et al. 2021). Each approach was evaluated for its technological readiness (TRL), potential impact, and applicability to the industry. Biobased construction materials were rated highly, with many products made from bamboo, wood, straw, and hemp already widely available. Other feedstocks including algae were mentioned for their potential, but only microalgae were briefly evaluated from a TRL perspective in relation to building integrated photobioreactors. The authors highlighted that the applicability and impact of any of 13 approaches remains largely dependent on both cost implications and local condition, but that ultimately the potential for accumulating CO_2 in the built environment is currently being underutilized.

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Every year over 1,500 billion bricks are manufactured globally, with 90% of production concentrated in China, India, Pakistan, Vietnam, and Bangladesh (Climate & Clean Air Coalition 2015). Bricks are generally made from a mixture of up to three types of clay mixed with water, compression moulded then fired in kilns at up to 1400 °C for between 10 and 40 h. A typical brick contains silica (50–60%), alumina (20–30%), lime (2–5%), oxide iron (5–6%) and magnesia (< 1%) (Punmia et al. 2005, p. 33) although the content and properties of an individual brick might vary considerably, reflecting local source material and manufacturing conditions. Firing bricks results in black carbon, CO_2, sulphur dioxide, and other pollutants being released into the atmosphere. The production of bricks produces 213 kg of CO_2 per tonne (10 kg m^{-2}) in high-income markets like the UK, and significantly more in low-income markets that may not have access to efficient production methods (The Brick Development Association 2021, p. 8). In Australia, about 50 manufacturers produce around $AUS 1 billion worth of bricks every year, although domestic production is falling due to increased energy costs (IBISWorld 2022).

Algae (microalgae and macroalgae) has been identified as one of the most effective mechanisms in sequestering atmospheric CO_2. Algae are farmed for a range of bio-products including food, feed, fertilisers, nutraceuticals, energy production, and as a feedstock alternative to petrochemicals to make plastics (Fabris et al. 2020; Levasseur et al. 2020). Algae play an important role in the development of the bioeconomy, in particular our transition to a low-emissions economy, meeting the growing demand for food security through more sustainable agriculture and fisheries, and the use of renewable and regenerative biological resources at industrial scale (Magnusson et al. 2016; Klavins and Obuka 2018, p. 174).

When marine macroalgae (seaweeds) are used to generate a high-value product, the biomass remaining after extraction can be valorised. Using the biorefinery approach, secondary and even tertiary products can be sequentially removed from the extracted residual biomass (Neveux et al. 2015; Lee et al. 2021). This has both economic and sustainability benefits as it becomes a zero-waste process. In Australia, agriculture and aquaculture industries have begun cultivating seaweeds for wastewater treatment and management. Seaweeds thrive in this nutrient rich environment and require regular harvesting, and growing evidence suggests that inland seaweed farming can produce an abundant and renewable source of carbon fixing biomass as seaweeds contain, on average, 25–30% carbon by dry weight (Chung et al. 2011, p. 881; Froehlich et al. 2019, p. 3096). Currently, harvested seaweeds are processed to extract value added molecules such as pigments, proteins, hormones, polysaccharides, and the remaining biomass is treated as residual waste. Our biorefinery research investigates alternative uses for this residual biomass and explores its potential for a variety of product applications in the construction industry.

Uses of seaweeds in construction: A brief overview

Australia's First Nation peoples have long used seaweeds for a variety of applications including medicinal purposes, for shelter and insulation, clothing, cooking and food preservation (Thurstan et al. 2018). In the mid-nineteenth century European settlers recorded Traditional Owners in South Australia using seaweed in roofs for waterproofing, wind-proofing and insulating dwellings. The authors also report evidence of the red seaweed *Eucheuma speciosa* being used in cement in Western Australia during the late nineteenth century. A wide variety of seaweed applications have been detailed by (Mouritsen et al. 2021), and (Yang 2012) recorded seaweeds and seagrasses used in the construction of buildings dating back to the seventeenth century along coastal areas of the U.K, Europe and the Jiaodong Peninsula, China. Yang also reported that boron and calcium alginate found in the seaweeds to be effective flame retardants, and the green seaweed (*Ulva*) has been found to have similar properties with another study reporting high heat insulation and heat capacity and claiming *Ulva* to be a 'brilliant flame retardant' (Hassan et al. 2008).

Seaweeds are a good source of lipids, starch, proteins, vitamins minerals, and unique sulphated carbohydrates such as carrageenan, alginate and ulvan (Mata et al. 2016; Prabhu et al. 2020; Msuya et al. 2022). A Scottish brick manufacturer used alginate (< 20%) as a bonding agent with small quantities of sheep's wool (</= 5%) as reinforcement in soil bricks, and tests found its addition increased compression strength (Galán-Marín et al. 2010). In another experiment, blocks including dried alginate from the stipes of seaweed showed increased flexural strength (Dove 2014). The compressive strength (1.64 N mm^{-2}) did not reach the level recommended by existing standards for unfired earth blocks (for example, New Mexico sets a minimum requirement of 2 N mm^{-2}) so these bricks were deemed unsuitable for commercial use. The authors did note the superiority of alginate extracted from the stipe of the seaweed as compared with the thallus; 'the stipe product will have a higher guluronic acid content and will consequently produce a stronger and more rigid gel network compared to the frond-derived products' (Dove 2014, p. 227).

Gaps and opportunities

The elemental composition of seaweeds means they can offer excellent sound and heat insulation, have significant heat capacity, are fully biodegradable and can offer strong carbon dioxide fixation (Jang et al. 2013, p. 83).

These characteristics suggest that seaweeds have significant potential as a construction material, yet despite there being evidence of seaweeds being used in construction and in weatherproofing for centuries, there have been relatively few recent studies that examine their potential for use in new building materials and products. For example, GENIALG is a pan European and industry-driven project established in 2017 to design high-yielding cultivation systems for two varieties of European seaweeds (*Saccharina latissima* and *Ulva)* for use across a range of products. Pharmaceuticals, nutraceuticals, functional foods, and bioplastics are nominated as primary targets for this initiative, while construction is not mentioned (GENIALG project 2022).

A systematic search of the Web of Science and Scopus databases conducted in May 2021 found only 31 papers focused on algae across the areas of construction building technology, civil engineering, and material science (composites and ceramics) (Rossignolo et al. 2022). These studies largely focused on the use of seaweeds and sea grasses for particleboards, polymeric and cemented composites, adobe, pavement, roofs, and facades, and only two studies using algae as an ingredient in adobe bricks were found. Three studies were concerned with the uses of *Ulva*, and all focused on its potential as a polymer reinforcement (Hassan et al. 2008; Barghini et al. 2010; Jang et al. 2013). Two of those studies failed to find any improvement in the performance of polymers using untreated *Ulva* fibres; however, one study found that pre-treating the seaweed with sulfuric acid was the most efficient method to remove impurities, enabling green seaweeds to be used as a reinforcement in bio-composites (Jang et al. 2013).

A 2022 state of the art review reported on a wide range of utilisations and discussed benefits across 'climate change mitigation and environmental sustainability, food consumption, animal feed additives, fish diets, bioplastic production, biofertilisers, biochar production, carbon sequestration tools, crop enhancers, antimicrobials, anti-inflammatory, anticancer, contraceptive, cosmetics, and skin care agents' (Farghali et al. 2022). Whilst presenting a comprehensive academic overview, there is both a notable absence and lack of enquiry into the potential uses of seaweeds in construction. A 2021 report on opportunities for developing the European seaweed industry failed to consider potential applications of seaweed in the building industry (Selnes and Giesbers 2021). This is consistent with a 2020 Agrifutures report on the seaweed market in Australia, which also failed to nominate the building industry as a potential market (Kelly 2020). This lack of enquiry to date is reflected by an absence of patent activity. A 2017 review of 288 patents relevant to construction biotechnology (specifically relevant to microbes, cement, concrete, and mortar) failed to identify any related to making use of algae for biomineralization and the authors highlighted this as an area in need of further exploration (Dapurkar and Telang 2017).

If we are to address climate change in a meaningful way, we need to find existing commercial markets that are currently dependent upon fossil sources of carbon and replace them with biogenic carbon. Given the massive size of the construction industry's carbon footprint, this should be a strong motivating force to transform it from a carbon source to an important carbon sink – using seaweed-based construction materials.

Designing with biology: An interdisciplinary approach

Our research team is composed of designers with skills in materials and practice-led research, scalable 1:1 prototyping and expertise in design practices that include product, fashion and textiles design. Our scientific team members bring expertise in algae biotechnology, biochemistry and bioremediation. Our aim has been to share knowledge and experience from our respective disciplines to foster new and creative approaches for sustainable materials design and the development of innovative algae-based products. We are combining processual design research methods (Tonuk and Fisher 2020) and design driven systems thinking to ensure the utilisation of algae as a sustainable material for carbon capture happens in connection with research that examines algae-based materials within real life ethnographies, specifically how they are perceived, understood, and encountered (Drazin and Küchler 2015). For example, we know that temporarily locking up atmospheric carbon in biomaterials that are used to make short life cycle products or that are designed for single use is not a sustainable solution (Penty 2019). Our research aims to broaden the scope of algae-based materials and product applications beyond single use or short-term biodegradable application by thinking through long-term relationships between end-users and algae-based products that can sequester atmospheric carbon for extended periods of time, aligning with circular economy principles as well as sustainable repair and reuse approaches (Ellen MacArthur Foundation 2022).

Biodesign, where it is historically connected to examples of biomimicry and biophilic design, asks us to approach relationships between design and nature differently, often in ways that decentre human experiences and that critique methods of designing that assume or work towards ecological control and biological mastery (Fletcher et al. 2019). Within this rapidly expanding field designing *with* biology (Myers and Antonelli 2012; Ginsberg and Chieza 2018) has given rise to new markets and industries driven by biotechnology alongside revolutionary advancements in product innovation, of which some examples are lab-grown meat, bio-based clothing, biodegradable furniture, through to the development of self-healing concretes and fillers for the building industry. Designing with biology is therefore happening at a range of scales, from a single cell through to a city. It can encompass genetically engineered bacteria that are designed to grow biodegradable materials for clothing and furniture, through to regenerative architecture that utilises organic waste and living microbes in the construction of buildings.

As the bioeconomy continues to grow and we transition from fossil-derived materials and products to bio-based alternatives, the integration of biological processes and the design of bio-based materials in architecture and the built environment requires an approach that goes beyond the confines and scale of the laboratory. Exhibitions, architecture festivals and design fairs are platforms to socialise innovative and experimental biomaterials, technologies and processes (Antonelli 2012). Demonstrators and 1:1 scale prototypes function as visual, tangible, and material provocations in these contexts that illuminate pathways for industry transformation, societal acceptance and most importantly encourages behavioural change. A key example of this is 'Hi-Fi' by David Benjamin and The Living studio, engineered ARUP and commissioned by the Museum of Modern Art (MoMA) PS1 in New York (Fig. 1). This temporary structure made from mycelium composite materials stood nearly three stories high. Where there has been considerable research published in academic journals on the potential applications of mycelium in packaging materials, furniture and acoustic panelling over the past 10 years (Almpani-Lekka et al. 2021), 'Hi-Fi' remains one of the most recognised and cited examples of myco-fabrication methods. The architectural pavilion demonstrated the structural potential of mycelium and myco-materials in the built environment (Dessi-Olive 2022). In doing so, it generated awareness and acceptance of novel mycelium construction products, and it captured social and economic interest in what was previously a nascent and experimental form of biomaterial production.

This study has so far discussed the advantages of utilising a biorefinery framework and the contributions this can make to decarbonising the building industry. It has presented an overview of historical and existing uses of seaweeds in construction and identified opportunities for the advancement of seaweed-based construction and building materials. It has outlined the value of interdisciplinary approaches that

Fig. 1 Hy-Fi by The Living / David Benjamin, with structural engineering by ARUP. Commissioned by the Museum of Modern Art (MoMA) PS1, New York 2014. Photo courtesy of The Living

Table 1 Biochemical composition of *Ulva* paste

Biochemical composition	Residual Ulva paste
Proximate analysis (as % wt.)	
Total solids	13.2
Moisture	86.8
Mineral content	5.3
Organic matter	7.9
pH	12.0
Higher Heating value (MJ/kg)	11.6
Appearance	dark-green paste
Protein[1]	1.0
Total lipids	0.1
Carbohydrates[2]	6.8
Ultimate analysis (as % wt. of total solids)	
Carbon	28.1
Nitrogen	2.6
Phosphorus	0.3
Oxygen	36.5
Hydrogen	4.6
Sulfur	2.2

[1] Protein as sum of total amino acids

[2] Total carbohydrates content determined by difference

connect design with science and contextualised these within the emergent and hybrid field of biodesign. It has also highlighted the role of 1:1 scale design prototypes and exhibition displays in generating social acceptance and encouraging consumer uptake of new biomaterial products in the build environment.

Materials and methods

Using the biorefinery approach outlined above, this research utilised residual biomass from aquaculture farming and investigated the application of this seaweed waste stream as a masonry material that could be incorporated into buildings, thereby contributing to decarbonising the construction industry and providing potential carbon storage solutions. The aim was to achieve a proof-of-concept seaweed brick at a comparable scale to a Besser brick, which measures 390 mm × 190 mm x 190 mm. The seaweed bricks would be used to build a design concept demonstrator for the 2022 Adelaide Biennial exhibition at the Art Gallery of South Australia. The demonstrator, functioning as a 1:1 scale architectural model, would be used to communicate the benefits of further advancing the materials science needed to develop seaweed-based construction products for the built environment.

Four design development phases were undertaken for the project in order to compare the advantages and disadvantages of working with wet and dry seaweed biomass, evaluate the bonding strength from a range of binders, determine an appropriate composite filler, and develop a scalable moulding technique and a curing process to fabricate the bricks. Design Phases 1- 4 outlined below are experiments from the perspective of the designers who have co-authored this paper, however we have used ‘Design Phase’ to describe our materials and methodologies to acknowledge disciplinary distinctions between design and science with regards to the meaning and use of the term ‘experiment’, and subsequently differences in both methods and intent.

In design, an experiment can be an open-ended inquiry that draws on subjective experience, or an exploratory undertaking using ethnographic approaches whereby something is made, often through non-standardised variables (Wilkes et al. 2016; Ginsberg et al. 2017; Malpass 2017). In contrast, the scientific experiment is structured around a repeatable and replicable method to test a hypothesis. Both are a different, disciplinary-specific methods of discovery and ways of generating knowledge. The materials and methods detailed below present a combination of ethnographic and subjective observations alongside relevant quantitative testing data. The test sizes produced were not undertaken using a specific standardised norm.

The design development was conducted using the green seaweed *Ulva ohnoi* – thereafter referred to as *Ulva* – which is a by-product derived from a biorefinery process. This process generates a liquid plant bio-stimulant as the primary high-value commercial product and the remaining carbon-rich paste is treated as waste. The biochemical composition of the ulva paste is detailed in Table 1. We tested the seaweed residue with a range of polysaccharide binders. These binders were chosen as they are used in bio-based material recipes and biomaterial cookbooks that are freely available. These include the CHEMARTS cookbook, a collaboration between the School of Chemical Engineering and the School of Arts, Design and Architecture, Aalto University (Pirjo Kääriäinen, Nina Riutta, Liisa Tervinen, Tapani Vuorinen & Aalto University, 2020) and Materiom, an open database of regenerative materials where both recipes and images are uploaded from an international community of scientists, engineers, and designers (Materiom 2023).

Design phase 1

In Design Phase 1 we dried and milled the *Ulva* into a powder (< 1 mm particle size). A total of 14 small-scale tests were undertaken with modified cellulose, starch, chitosan and carrageenan binders in varying combinations in order to observe bonding strength and to understand how the seaweed reconstituted (see Table 2). Each test used 50 g of *Ulva* powder producing samples that measured 35 × 35 × 10 mm.

Table 2 Design phase 1, binder testing

Design Phase 1														
Test ID	*Ulva* powder	Water	Main Binder		Binder 2		Binder 3		Binder 4		Binder 5		Binder 6	
	(g)	(g)	Type	(g)	Type	(g)	Type	(g)	Type	(g)	Type	(g)	Type	(g)
1	50	60	CMC 6% w/w	15										
2	50	59	CMC 6% w/w	15	MFC10%	6								
3	50	140	Carrageen an	3	Locus bean gum	0.5								
4	50	120	Starch (Mung bean)	15	Citric acid	1.2								
5	50	160	Glucano delta lactone	3	Tannie acid	3	Calcium chloride	3						
6	20	200	Urea	6	Dialdehyde starch	1	Glycerine	4						
7	50	190	Glucano delta lactone	1	Tannie acid	1	Calcium chloride	1						
8	25	120	CMC 6% w/w	23	Chitosan	25								
9	5.5	0	MFC 2%	23.5										
10	25	185	CMC 6% w/w	15	Chitosan	25	Glucano delta lactone	0.5	Tannie acid	0.5	Calcium chloride	0.5		
11	25	160	CMC 6% w/w	15	Chitosan	25	Carrageen an	1.5	Locus bean gum	0.25				
12	50	114	CMC 6% w/w	50	Chitosan	5	Calcium chloride	4						
13	50	140	CMC 6% w/w	20	Chitosan	5	Cationic starch	10	Corn starch	10	Citric acid	1	Tannie Acid	1
14	50	75	Sodium Casinate	10	Borax	5	Glycerine	4						

The sample tests were made by combining the *Ulva*, binder combination, and water to form a dough which was then rolled out to a thickness of 10 mm and cut with a non-standardised 35 × 35 mm square mould.

Design phase 2

Design Phase 2 used wet *Ulva* paste derived from the same biorefinery process and we selected 4 binder ingredients from Design Phase 1 – Carboxymethyl cellulose (CMC), calcium caseinate, starch, and microfibrillated cellulose (MFC) to test with the *Ulva* paste. The *Ulva* paste has a water content of 86% (drying 100 g of the AP yielded approximately 14 g dried mass). We increased the non-standardised testing scale from the initial testing size of 35 × 35 × 10 mm up to 90 × 90 × 30 mm and used the same quantity of *Ulva* biomass and binder, normalised for moisture content (e.g. 350 g of wet *Ulva* equals 49 g dried *Ulva* biomass). We also tested an additional binder combination using calcium caseinate, which was widely used until the 1940's as a strong water-resistant adhesive before the introduction of cheaper petrochemical adhesives.

Each test was weighed on the day of pressing and de-moulding the sample before being placed onto a mesh rack so that all sides were exposed to airflow. The samples were turned once on day 3 and left to airdry for a total of 14 days within a stable temperature range between 21–23 °C. The samples were dry to touch by day 7 but were left for another 7 days. We looked to take advantage of the water content already in the residual biomass and work towards being able to predict and control the level of shrinkage. To do this, aggregates were added to the Ulva paste that would also work as filler material and assist with drying. Our tests included hemp fibres, wool fibres, brewers spent grain (BSG), banana leaf fibres, golden kelp (*Ecklonia radiata*), and crushed oyster shells (Fig. 3). The Test IDs in Table 3 correspond with the test specimens numbered in Fig. 2.

Design phase 3

Design Phase 3 focused on increasing the scale of our material samples, determining the *Ulva* paste to aggregate ratio and designing a mould to produce larger 1:1 scale masonry brick pieces. We began by using a circular shape mould that allowed us to test a hand pressing technique which involved packing the material into a seamless cylinder, then apply even weight and pressure via a tamp, before pushing out the sample. These circular samples were 150 mm in diameter and left to air dry for 7 days. Sample 22 was 40 mm high, weighed 1296 g when pressed and this reduced to 843 g when dried. Sample 23 was 50 mm high, weighed 1446 g when pressed and reduced to 997 g when dried (Fig. 3).

We determined that oyster shells were the desirable composite aggregate to proceed with for the purposes of producing a design concept demonstrator. Oyster shells have naturally strong properties due to their calcium carbonate content (Gansheng et al. 2021); we were also able to crush and mill them into different grades which allowed us to formulate and adjust a material recipe that integrated well with the *Ulva* and CMC binder, whilst also reinforcing the material's overall strength.

Oyster shells were sourced in two stages from Australia's Oyster Coast and a co-operative of oyster farms along the New South Wales coast. During the first stage, 500 kg of shells, a mixture of Pacific and Sydney Rock oysters, were acquired from a commercial dispatch centre where the oysters were being cleaned, sorted, and shucked ready for sale in supermarkets and at other various food retail outlets. This meant our first batch of shells were predominantly oyster shell lids and were a waste by-product from the oyster farming industry that would have otherwise ended up in landfill.

In order to prepare them for crushing and making aggregate, we hired a mobile cool room for a week and setting up a rotation system of washing, scrubbing, and sun-bleaching the shells to remove any residual oyster tissue and other forms of biofouling. No pyrolysis process was undertaken. Our method involved soaking the shells in a detergent bath, followed by hand-scraping, and scrubbing the shells, rinsing, and flushing the shells in large, perforated tub before turning them out onto mesh metal racks to dry and bleach in the sun.

In the second stage, 600 kg of oyster shell waste was sourced directly from the farms, which meant that there were significantly more oyster cups than lids, which then required a different system to be developed for washing and cleaning. This method involved soaking the shells in a detergent bath, followed by a 5 min tumble rotation in a concrete mixer which loosened and removed dirt and debris. The shells then were sandwiched between two metal mesh sheets and pressure washed, before being left in the sun to airdry on racks. They were exposed to sun bleaching for five days, rotated regularly to ensure even exposure, and then hand-sorted to remove any closed shells or pieces with significant biofouling (Fig. 4).

Once the shells where clean and dried they were mechanically broken down using a rammer compactor to range of particle sizes between < 1– 7 mm. The aggregate was graded manually by hand sieving using non-standardised sieving equipment. At the completion of the project, we had developed a method of cleaning and crushing which enabled us to process over 1100 kg of oyster shells.

Design phase 4

The iterative testing undertaken in Design Phase 4 was to develop a comprehensive understanding of the relationship between the material, the design of the brick mould, and

Table 3 Design Phase 2: Testing binder and aggregate combinations

Design Phase 2														
Test ID	*Ulva* powder	Fibre			Aggregate			Main Bulider		Water	Binder 2		Binder 3	
	(g)	Type	Length (mm)	(g)	Type	Size (mm)	(g)	Type	(g)	(g)	Type	(g)	Type	(g)
1	250							CMC 6% w/w	39	5	MFC 10%	16		
2	250							CMC 6% w/w	60					
3	250							Sodium Caseinate	8	46	Borax		Glcyerine	2
4	250							Guargum	3.6	56				
5	250							CMC 6% w/w	39	5	MFC 10%	16	Sodium lauryl sulfate	1
6	250							Starch (mung bean)	15	120	Citric acid	1.2		
7	250	Corn husks (dried)	30×3	4				CMC 6% w/w	39	5	MFC 10%	16		
8	250	Wool	8–10	5				CMC 6% w/w	60					
9	250	Banana leaf (dried)	30×3	5				CMC 6% w/w	60					
10	250	Hemp	8–10	5				CMC 6% w/w	60					
11	250				*Ulva* dried (unground)	5–15	150	CMC 6% w/w	60					
12	250				Brewersspent grain	2–4	80	CMC 6 % w/w	60					
13	1000				Brewers spent grain	2–4	320	CMC 6% w/w	240					
14	250				Oyster shell	< 30	180	CMC 6% w/w	60					
15	250				Oyster shell	< 10	180	CMC 6% w/w	60					
16	250	Kelp (dried)	< 10	80				CMC 6% w/w	60					
17	250	Kelp (dried)	< 30	80				CMC 6% w/w	60					
18	250	Kelp (dried)	< 10	40	Oyster shell	< 30	90	CMC 6% w/w	60					
19	250	Kelp (dried)	< 30	40	Oyster shell	< 10	90	CMC 6% w/w	60					
20	250				Oyster shell	< 10	180	CMC 6% w/w	60			Chitosan	10	
21	250				Oyster shell	< 30		Starch (mung bean)	7.5		60	Citric acid	0.6	
22	250	Kelp (dried)	< 30	40	Oyster shell	< 30	90	Starch (mung bean)	7.5		60	Citric acid	0.6	
22	400				Oyster shell	< 10	800	CMC 6% w/w	96					
23	400	Kelp (dried)	< 30	150	Oyster shell	< 10	800	CMC 6% w/w	96					

Fig. 2 Design Phase 2. Selection of specimen samples testing bonding and shrinkage with organic aggregates and fillers: hemp fibres, wool fibres, brewers spent grain (BSG), banana leaf fibres, golden kelp (*Ecklonia radiata*), and crushed oyster shells. Specimen sample numbers correspond with Test IDs in Table 3. The Test IDs in Table 3 correspond with the test specimens numbered in Fig. 2. Photo: Robin Hearfield

Fig. 3 Sample 22 (left) Sample 23 (right). Sample numbers correspond with Test IDs in Table 3. Photo: Robin Hearfield

the drying method. We focused on designing larger scale moulds, testing different geometries and ways of partially disassembling the moulds in order to expose the pressed material to adequate airflow, whilst still supporting the weight of the material in early drying stages.

A range of angular ‘zigzag’ geometries were tested alongside moulds with curved surfaces, a 300 × 300 × 300 mm cube, and a series of rectangular prism moulds up to 400 × 1150 × 80 mm were also tested. At this scale and volume, the pressed form had the potential to slump from the weight of the wet material, so moulds were tested and fabricated that could be disassembled incrementally as the material dried. For example, a 300 × 300 × 300 mm cube mould was designed with palings that could be removed incrementally to allow airflow and drying to occur while the corners were still holding the material in shape (Fig. 5 and 6).

The scale up in our testing coincided with some of the most disastrous flooding events ever recorded by the Australian Bureau of Meteorology. The east coast of NSW was inundated with rain over the summer months in 2021 and early 2022, and the hot, wet, and humid conditions coinciding with the increased scale of experiments meant we needed to install a temperature and humidity-controlled chamber for curing and drying the bricks. The

Fig. 4 Cleaning, washing, and sorting oyster shells. Photo: Kate Scardifield

chamber measured 2.0 m (length) by 3.6 m (width) by 2.7 m (height), lined and sealed with builder's plastic and insulated with additional foam sheeting. We installed a commercial dehumidifier (Airrex ADH1000) within the chamber. Once the bricks were pressed, they were transferred into the chamber for a 14-day period. The bricks were rotated and turned at Day 5 and Day 10 to ensure the drying environment worked to draw out the moisture slowly and consistently to avoid cracking. After the bricks were dry, a calcium caseinate coating was applied to the surface of the bricks with a drying time of at least 12 h between coats. Applying this coating created a tough surface and increased the water resistance of the brick surface.

Results

Design phase 1

The carboxymethyl cellulose (CMC) and starch tests dried uniformly and showed between 6—8% shrinkage across the samples. The carrageenan and chitosan tests had greater shrinkage and some cracking was also observed on these samples. The CMC and starch binders produced samples that bonded strongly together and were robust enough to drag across a bitumen pavement without snapping or crumbling. Whilst both the CMC and starch seemed to have similar qualities, the CMC was considered preferable to the starch.

Design phase 2

We developed an understanding of the differences between working with the *Ulva* by-product once it has been dried and milled and working directly with the paste-like wet *Ulva* by-product. The wet *Ulva* paste increased the water content of our test recipes, and we encountered significant shrinkage in these samples, for example the starch and CMC binder tests both shrunk over 30%. We attempted to reduce the water content by hand-wringing the *Ulva* paste through a silkscreen mesh prior to mixing. Our goal was to achieve a stable material cast at a scale comparable to a Besser brick, so whilst the shrinkage was lesser in Design Phase 1 than in Design Phase 2, in order to increase the scale of our brick prototypes it was preferrable to work with the residual biomass in a wet state to improve the sustainability and economics of the process.

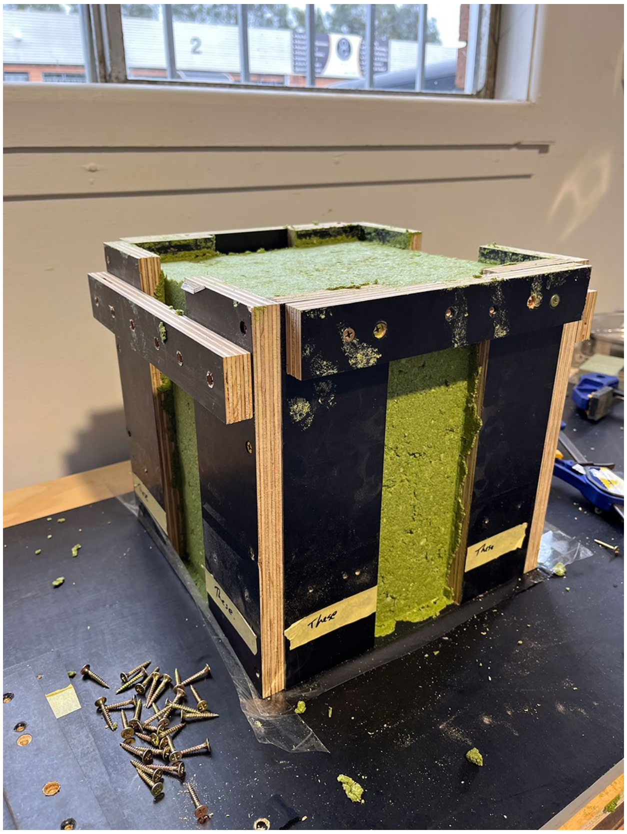

Fig. 5 300 mm cube mould with removable centre palings. Photo: Kate Scardifield

Fig. 6 300 mm cube demoulded and partially dried. Photo: Kate Scardifield

The calcium caseinate, CMC and starch all behaved quite similarly at this testing scale, and the hand feel of the material, shrinkage and distortion were all comparable. Of the aggregates tested, the BSG and oyster shell were revealed to be the most promising. Both the BSG and oyster shells were waste by-products we sourced from a local brewing company and an oyster farming co-operative. The *Ulva* and oyster shell composite had negligible shrinkage and dried quickly. The BSG had some shrinkage (~3%) but was also prone to mould growth as it took a longer time to dry.

Design phase 3

Cylinder tests 22 and 23 (see Fig. 3) with a height of 50 mm had dried in under 7 days, and we drilled through Test 22 to confirm this. We used this result to assume we could double the thickness of our sample and expect a drying time of approximately 14 days. For our final moulds we ensured that the maximum thickness between two edges was no more than 100 mm (Fig. 7) and created two voids in our brick moulds to increase surface area.

The water content was reduced by adding the binder directly to the *Ulva* paste rather than hydrating the binders in water. This resulted in a drier mix which helped reduce slumping and sped up the drying process. Finding the right balance for the mix was crucial as a mix that was too dry resulted in crumbly material, while too wet would slump and deform during the drying process.

Our final brick moulds allowed the material to be packed into the mould recess, flipped over 180 degrees onto a board, the mould was then partially disassembled and lifted off the pressed brick, which was then able to stand freely on its drying board. Figure 8 shows one of five final moulds used to produce the bricks. Once pressed, the bricks were then moved to the temperature and humidity-controlled chamber for 14 days.

Design phase 4

A total of 95 seaweed bricks were pressed and cured, transforming seaweed biomass into solid, strong, and stable masonry pieces (Fig. 9 and Fig. 10). The bricks built a free-standing column measuring 900 mm in diameter and close to 3 m high (Fig. 11). No mortar or adhesives were used in the joining of the bricks, instead they were held under tension by threading polypropylene strapping through the recesses

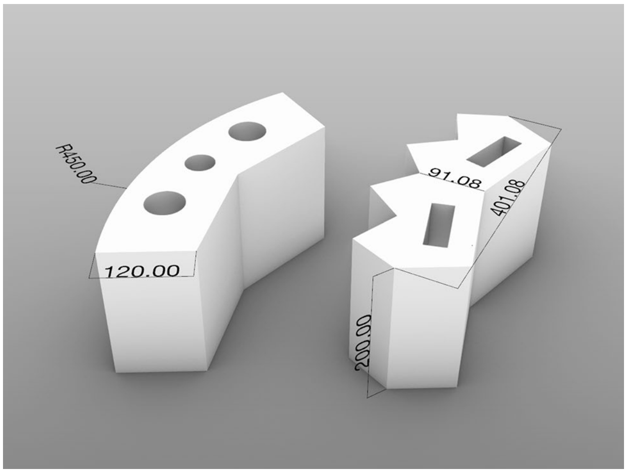

Fig. 7 Curved brick (left) and zigzag brick (right) renders. Photo: Nahum McLean

and tensioning this to a central truss support. The design concept demonstrator was presented at the Art Gallery of South Australia as part of the 2022 Adelaide Biennial of Australian Art, showcasing an architectural application for residual seaweed biomass and communicating its potential for use as a building and construction material. The exhibition attracted over 155,000 viewers over 95 days in 2022 and included seaweed specimens loaned from the State Herbarium of South Australia, helping to contextualise the potential of the research to developing seaweed industries along the southern Australian coastline.

The column's 'fluted' design is a historical architectural reference to classical columns which hold up the porticos and detail the external facades of some of the world's most prominent civic and government buildings. The unconventional 'zigzag' geometry of each brick in the demonstrator column is intended as modular design feature. This geometry references interlocking corner profiles which allow for variations in the positioning of block masonry pieces, as well as joinery solutions that don't require mortar or additional adhesives (Fig. 12). Each brick piece in the demonstrator had an average dry weight of 9.5 kg and was hand-packed and pressed from one of three registered form-ply moulds. Minor irregularities in the material, be it the consistency and grade of the oyster shell aggregate, and the various hands that packed each mould has meant that each brick is to some extent unique and irregular in its edition.

Discussion

Processing *Ulva* into a powder once it has already dried proved to be challenging, it was time-consuming and requires industrial milling machinery. Sourcing the *Ulva* biomass in a wet form allowed us to add the binders directly

Fig. 8 Final 'zig-zag' brick mould used to press angular seaweed bricks. Photo: Robin Hearfield

Fig. 9 Seaweed bricks, 3 pieces measuring 800 × 250 × 400 mm each. Photo: Robin Hearfield

Fig. 10 Seaweed bricks, 6 pieces, 900 mm outside diameter, 200 mm height. Photo: Robin Hearfield

Fig. 11 Demonstrator installed at the Art Gallery of South Australia. 900 mm outside diameter, 2600 mm height. Photo: Saul Steed

Fig. 12 Seaweed bricks, 5 pieces. Photo: Robin Hearfield

to the *Ulva* paste, however managing shrinkage without the need for adding large amounts of an aggregate became apparent during Design Phase 2. The dry matter content (DMC) of the *Ulva* biomass can be increased from 14 to 25–30% through hand-wringing the *Ulva* paste in a silk screen bag, however this is still below the DMC of the recipes tested in Experiment 1 which had 40% DMC. Manually squeezing the biomass reduces the water content of the *Ulva* paste which speeds up the drying process. However, the shrinkage rate was 20%, less than the 30% achieved in Design Phase 2, but far greater than the 6–8% achieved in Design Phase 1. *Ulva* is already being dried and milled at scale in north Queensland to extract biocomponents with high value applications. Results from squeezing the *Ulva* paste suggested that there are further opportunities to explore, such as partially drying the *Ulva* paste to around 40–50% DMC to negate the need for heavy machine processing, with another likely benefit being a reduction in overall shrinkage. Partially drying could also help to unlock latent properties from the polysaccharides in the biomass, increase its binding properties, and reduce the amount of additional binder that is required. During the drying process hydrogen bonds are formed between the hydroxy groups of cellulose chain network resulting in extensive polymer chain and strength. Also, the residual ulvan remaining in the biomass will lead to covalent crosslinks thus contributing to tight physical interactions (Robic et al. 2009).

Using oyster shell waste as an aggregate in the bricks gave some additional strengthening properties, however the disadvantages of incorporating shell waste are in the costs and extensive labour needed to clean the shells and remove biofouling. The growth rate of oysters is significantly slower than macroalgae and seaweeds, indicating that the volume of organic waste available from the oyster farming industry will not be comparable to the volumes of residual biomass generated by the steady growth of the Australian seaweed industry. Our experiments identified opportunities to explore other bio-based aggregates and composites for seaweed construction products that align with renewable and regenerative principles underpinning our research.

Efforts to facilitate comparisons of the environmental impacts of construction and building products exist, such as the Construction Material Pyramid developed by the Centre for Industrialised Architecture (CINARK) at the Royal Danish Academy. The digital version of the pyramid calculates that a cubic meter of fired clay bricks has a global warming potential of 528.6 kg CO_2eq, while unfired clay bricks produce only 93.6 kg CO_2eq, less than one fifth of that produced by the single-fired brick (Centre for Industrialised Architecture (CINARK) n.d.). These comparisons are useful to note the high embodied energy in fired bricks versus the lower embodied energy of unfired masonry products. Although surpassed in performance by modern materials raw earth bricks remain an important building material, particularly in low-income countries (Dove 2014). The seaweed bricks produced in this study were not fired, and instead cured over a 14-day period in an environmental chamber. A quantitative comparison of the production costs and embodied energy of seaweed bricks against commercially available clay bricks is outside the scope of this study, however we note that such a comparison would be a key subject for future research. Earlier studies have investigated the potential of sulphated polysaccharides to improve the mechanical strength and durability of traditional unfired raw earth blocks (Galán-Marín et al. 2010; Dove 2014) The incorporation of alginate into bricks has been demonstrated to improve the compression and flexural strength. However, the magnitude of increase was observed to be dependent on both the type of alginate and the type of soil utilised, indicative of possible chemical interactions.

There is a need to explore manufacturing alternatives that are not energy intensive in order for seaweed construction products to have additional value-adding benefits and potential GHG savings. Seaweed is fast growing, absorbs carbon and can play a significant role in efforts to mitigate climate change. A quantitative assessment of the $C0_2$ captured per brick, and the potential to utilise other sources of seaweed biomass (e.g. *Sargassum)* have been identified as key areas for future research. As naturally occurring land-based carbon sinks such as the Amazon is cleared and coastal ‘blue carbon’ systems (mangroves, salt marshes, and seagrass meadows) are increasingly impacted by climate change, the importance of diversifying the places and spaces in which to sink atmospheric carbon is becoming increasingly important. Our research is finding ways to use seaweed to manufacture longer lasting products that lock carbon away. The use of seaweed components such as alginates in food and feed do not offer extended periods of carbon removal, as once the food or feed is metabolised, the carbon returns to the atmosphere. This is also the case with biofuels and cosmetics, whereas the carbon in a building material remains out of the atmosphere until it is demolished.

Creating seaweed bricks could have sustainability benefits across numerous metrics and the research presented here is the result of a collaboration between designers and scientists working to address the social implications and potential impacts of algae-based product uptake beyond the laboratory. Treating wastewater with macroalgae contributes toward UN Sustainable Development Goal 6, to ensure access to water and sanitation for all. Using a biorefinery framework for the cultivation and procurement of biomass used in building and construction products can contribute to goals 12 and 14, by promoting the efficient use of natural resources and by using marine resources for sustainable development.

Although the results of our design experiments using seaweed as a construction material are promising, much research remains to be completed. In particular, to meet industry regulations and pass mechanical tests, seaweed building products must meet fire resistance standards. While the properties of algae suggest that it is possible to develop products that are fire-resistant, antimicrobial, mould-resistant, thermally efficient, and durable over time, these properties must be tested and proven effective before they can gain widespread acceptance in the construction industry. As this is happening it is crucial to capture social and economic interest in novel seaweed-based construction products and get the public on board and behind the transition from fossil derived materials and products to more sustainable biogenic product solutions.

Authors contributions All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Kate Scardifield, Nahum McLean, Unnikrishnan Kuzhiumparambil and Peter J. Ralph. Literature review: Geoff Isaac, Kate Scardifield and Tim Schork. Manuscript preparation: Geoff Isaac. Writing – original draft preparation: Kate Scardifield, Nahum McLean, Unnikrishnan Kuzhiumparambil and Peter J. Ralph. Writing - review and editing: Kate Scardifield, Nahum McLean, Unnikrishnan Kuzhiumparambil, Peter J. Ralph and Nicolas Neveux. Funding acquisition: Kate Scardifield. Resources: Kate Scardifield, Unnikrishnan

Kuzhiumparambil, Peter J. Ralph and Nicolas Neveux. All authors read and approved the final manuscript.

Funding Open Access funding enabled and organized by CAUL and its Member Institutions This work was supported by the UTS 2027 Cross Faculty Collaboration Scheme and the Australia Council for the Arts, its arts funding and advisory body (Grant numbers PRO21-12590 and G-22–335823).

Data availability The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests The authors have no competing interests to declare that are relevant to the content of this article.

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