

Evaluating the Architectural and Environmental Potentials of a Mussel/alginate-based Marine Bio-composite

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Abstract. Scaling a circular and net zero building practice requires increasing the quantity and diversity of locally available biobased materials. Where the increased use of traditional large, woody and fibrous biomass such as virgin timber risks over-exploitation and biodiversity loss, new circular material flows based on aquatic biomass (micro and macro algae, shellfish, and eelgrass) can open new opportunities for architectural design and expression, regional connection and architectural agency. This paper explores one such material, a mussel-shell/alginate-based bio-composite, placing focus on its architectural performance and examining its suitability as an architectural cladding material. The research combines material formulation, mechanical and environmental testing, digital design methods and hybrid fabrication to develop and demonstrate a full-scale panel system.

Keywords. Marine Biomaterials, Polymer Composites, LCA, Material Systems, Digital Fabrication

1. Introduction

To achieve its ambitions of circular and net zero buildings by 2050, the Architecture, Engineering and Construction (AEC) sector must maximise the use of alternative bio-based building materials. However the advancement of 'cultivated construction' - the use of local grown or farmed materials, has to date maintained a terrestrial bias reflecting architecture's historical land-based material palette and industrialised building systems. As the global demand for mass timber is already accelerating beyond

sustainable supply (Oorschot et al 2023), and biomass generally becomes the focus for increasing inter-industry competition, finding ways to increase and vary the total amount of biomass available to architecture becomes critical.

This paper describes research exploring the use of aquatic 'blue' biomass to create architectural panel elements. The term blue biomass encompasses marine and aquatic biomass which may be cultivated, residual or invasive. It includes photosynthetic organisms such as seaweeds and microalgae that utilise solar energy to sequester CO₂, as well as mussels and oysters that mineralise carbon into shells. This biomass can be utilised in an inert, dried or processed state or used as living material to enact a biotransformation process such as bioremediation (Nicholas et al 2025). Where the monoculture-based farming of timber has reduced biodiversity and depleted the earth, cultivation of blue biomass can be a means for ecosystem regeneration: it does not require fertilizer or pesticides and can increase biodiversity while removing excess nutrients and contaminants from aquatic ecosystems.

To date, the majority of research into aquatic biomaterials has occurred outside of architecture, focussing on pharmaceutical, fuel and food applications, and has placed emphasis on laboratory scale fabrication and performance properties linked to biocompatibility and recyclability. Within architecture, a very limited quantity of state of the art research includes work exploring the recyclability of alginate-based materials (Rech et al 2023), developing tile and brick applications with shell-based materials (Shao et al 2024), and testing blue biomass as a partial substitute within existing materials (Bekkeri et al 2024). What remains largely unexplored is the architectural potential of blue biomass' dual role as a construction material and an ecological actor; as a systemic resource: one that simultaneously reconfigures material sourcing, design opportunities, fabrication processes and environmental performance; and as a scalable proposition. Part of realising this potential is investigating the role played by geographic origins and processing flows of blue biomass, whether cultivated or cascaded.

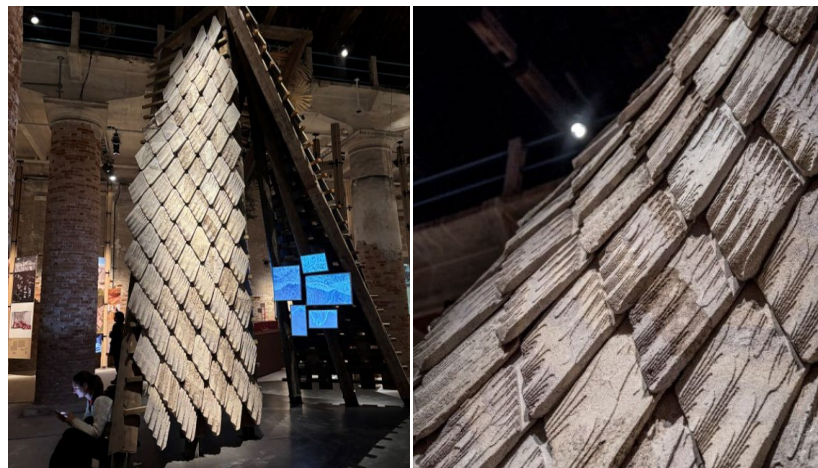


Figure 1. *Local Resource / Global Knowledge* installation at the Venice Architecture Biennale 2025. Left: Overall installation structure. Right: Detail of the panelised façade

This paper describes an almost entirely marine-based biopolymer composite material. We firstly detail this material and its sourcing, then outline the fabrication and evaluation methods used to make the panels and assess their performance in response to water, fire, loading and sustainability. The paper then describes the demonstrator 'Local Resource/Global Knowledge', a full-scale panelised façade (Figure 1), and the digital design methods used to specify desired material properties and geometries for the panels. Lastly, we assess the sustainability of the panel element using LCA.

2. Methods

2.1 MATERIAL COMPOSITION

An alginate gel formulation is prepared combining water, sodium alginate powder (12% relative to water content, sourced from Sapore Puro, Italy) and glycerol, a byproduct of biofuel production (5% relative to water content, sourced from Novadan, Denmark). Hammer-milled mussel shell sourced from the ocean bottom (aggregate size 0.7-2mm, Danshells, Denmark) hammer milled mussel shell sourced as processing waste from Consorzio Cooperative Pescatori del Polesine O.P. S.C.Ar.L., Venice (maximum aggregate size 0.6mm), and powdered eelgrass (sourced from MønTang, Denmark) are then incorporated into the gel. After casting and postprocessing, the material is sprayed with a 10% CaCl₂ solution to induce ionic crosslinking between the alginate polymer networks near the surface.

2.2 MATERIAL TESTING

Preliminary tests were conducted to evaluate a range of architecturally relevant material properties. Compression testing is conducted using a Mecmesin Omnitest 50. The testing procedure follows the ASTM C39/C39M standard and is conducted using moulded cylindrical samples of 100mm diameter and 200mm height. Water absorption is assessed via immersing moulded cylindrical samples of 100mm diameter and 60 mm height. Samples are immersed for 5 minutes then surface dried and weighed. Samples are then re-immersed for additional 5-minute increments until the weight remained constant. Fire resistance is evaluated by exposing a moulded cylindrical sample of 100mm diameter and 60 mm height to a direct flame of 450 degrees for increments of 1 minute for a total of 3 minutes. Material erosion is measured to assess thermal decomposition resulting from flame exposure.

2.3 DIGITAL DESIGN AND FABRICATION.

Panel design and material allocation is developed in Rhino3D and grasshopper. Casting processes are hand-based. Thin sheet vacuum formed moulds are used for casting. After demoulding cast panels are CNC milled. It was established that panels of scale 30*60*6cm could be demoulded after 1 day and were machinable, but not fully dry, after 7 days. After machining, panels fully evaporated excess moisture after an additional 7 days.

2.4 LCA

The sustainability assessment is based on a prospective LCA (Arvidsson et al 2024) conducted for the A1 (resource extraction), A2 (transport) and A3 (manufacturing) phases, using the ReCiPe MidPoint calculation method. The functional unit selected is 1 sqm of panel manufactured with the bio-composite material system developed. The manufacturing process assessed is extrapolated to be that of a small SME, similar in scale and organization to current companies manufacturing blue biomass products such as Sould.dk and mineralfox.com.au.

The assessment makes two assumptions. Firstly, that mussel cultivation is a no-inputs culture in Denmark and Venice, with no addition of fertilizer or pesticides to support growth. Secondly, that impacts associated to the machinery needed for the cultivation, mixing, and manufacturing are not considered. As equipment is used for the manufacturing of a great number of panels, their outlay renders the associated impacts negligible. However, the energy used by the machinery is considered, as well as water consumption.

3. Biocomposite Material Development

Biopolymer composites are material systems that combine a binder with multiple other materials. They are particularly suited to models of material production that emphasise locality and valorisation processes, and which do not assume the ready availability of standardised materials. For this reason, rather than aiming to identify a single optimal recipe, working with biopolymer composites emphasises logics of variation and substitution (Nicholas et al 2024).

During initial material development, formulations with varying ratios of six components were evaluated. These combined ground mussel shell at two particle-size ranges and powdered eelgrass as fillers; an alginate gel as binder; and calcium chloride as cross-linker. The alginate gel itself comprises water as the solvent, sodium alginate as the binding polymer, and glycerol as the plasticiser. Evaluation of these recipe formulations focused on three aspects. Firstly, maximising the overall quantity of mussel shell in the recipe. Secondly, to reduce water content while keeping viscosity within boundaries that allowed for castability and printability as potential fabrication methods. Lastly, to achieve distinct visual difference across recipes by activating the ratio of eelgrass and the type of mussel shell used, so as to support later material design strategies. The colour of mussel shells is influenced directly by environmental factors (Williams 2016). The development process resulted in an array of five castable material recipes with distinctly different visual expression (Figure 2).

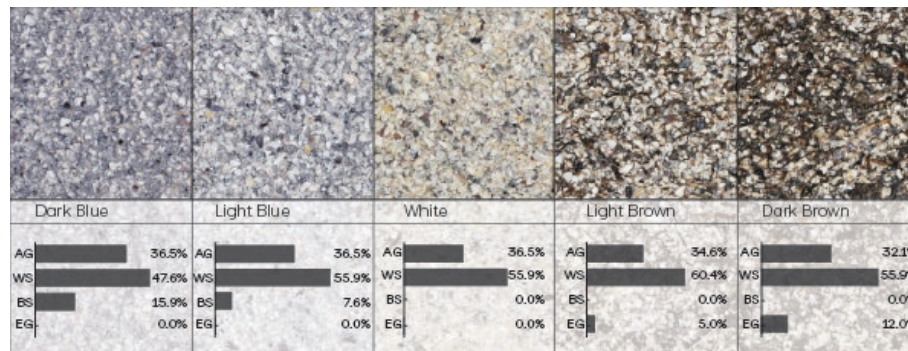


Figure 2. The impact of varying the ratio of eelgrass and specification of mussel shell on material expression. (AG: 12% Alginate Gel, WS: White Danish Shell, BS: Blue Venetian Shell, EG: Eelgrass)

4. Assessing Material Properties

The 'white' version of this material was chosen as representative of the material system and evaluated for compressive strength, water absorption, and response to fire.

4.1. RESULTS OF COMPRESSION TESTING.

Compression testing of three samples recorded a maximum load of 10,855 N and a mean load of 8,605 N (Figure 3). This corresponds to a maximum compressive strength of 1.38 N/mm² and a mean compressive strength of 1.08 N/mm², results comparable to the compressive strength of hempcrete, compressed earth or unfired clay blocks.

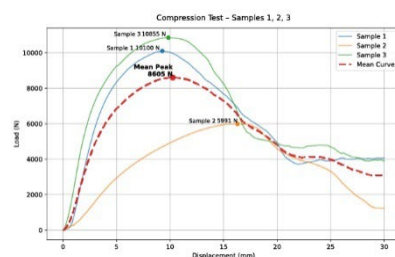


Figure 3. Left: Stress strain curves generated by experimental samples, demonstrating compressive behaviour. Right: Experimental setup

4.2. RESULTS OF IMMERSION TESTING

Three samples were immersed in water. After 5 minutes they recorded an average 22% increase in weight, and after 30 minutes their weight stabilised indicating that maximum saturation had been reached. The average water absorption across the three samples was 29.1% (Figure 4). The alginate exposed to the Calcium chloride creates a hydrophilic skin around the object, which swells as it absorbs water. When this skin breaks, the material begins to deteriorate.

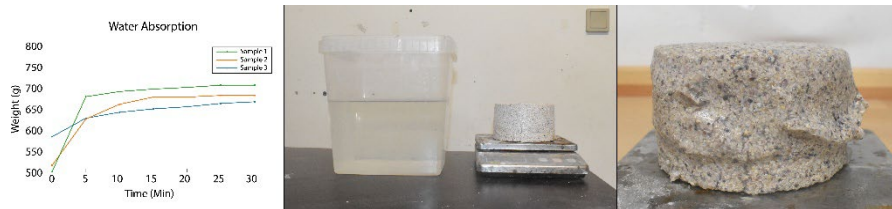


Figure 4. Left: Water uptake curve generated by experimental samples, demonstrating water absorption behaviour. Right: Experimental setup

4.3. RESULTS OF FIRE TESTING

One sample was exposed to fire in a controlled setting. When exposed to flame the material smokes slightly and calcinates, creating a mix of calcium carbonate and ash on the surface of the sample. After each increment of 60 seconds the ash is removed and the remaining thickness measured. The average decrease in diameter is 8.85 mm (Figure 5).



Figure 5. Left: Diameter change curve generated by experimental sample, demonstrating fire erosion behaviour. Middle: Experimental setup. Right: Result after 60 seconds exposure.

5. Demonstrator

The materials and methods described above are applied to the design and fabrication of the installation 'Local Resource / Global Knowledge', a 6.5m high tower exhibited as part of the Venice Architectural Biennale 2025: Intelligens. Natural. Artificial. Collective. The installation is a collaboration between CITA, 3XN architects and GXN research. It consists of three biogenic facades, one of which is clad in 104 diamond shaped shingle-like tiles made from the mussel shell / alginate bio-composite.

5.1. DESIGN PROCESS

The façade composition draws on the material's potential for differentiated colour expression and the directional logic introduced by the overall structure's twisting geometry. The digital design process allows the coordination of geometry, colour and orientation across the façade, the assignment of those parameters to individual panels and their interpretation by human makers during the casting process.

Within the digital model, a control surface is subdivided into diamond shaped panels. A region-based approach is used to assign colour palette and panel thickness to each panel. To assign colour, five vertical regions are defined. Each region is assigned a colour palette, either blues (3 colours), browns (3 colours), or mix (5 colours), as well as a specific number of colour bands, either 3, 5, or 7. The vector orientation of these colour bands within a given panel is defined using an inverse

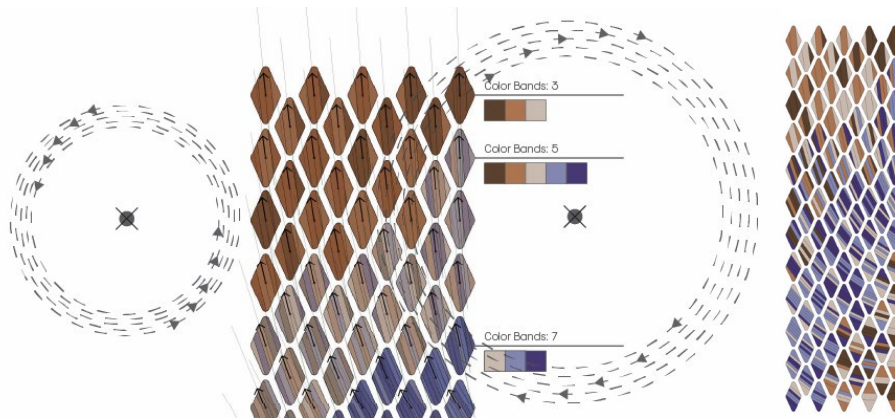


Figure 6. Segment of the façade design model showing coloured banding and specification of banding orientation.

distance weighting approach that references the location of multiple point charges positioned by the designer. A colour from the assigned colour palette is randomly allocated to each band within the panel. Adjacent bands can be assigned the same colour, reducing the impression of regularity. The result is a wave of colours that vertically transition from browns to blues to browns as the cladding plane twists (Figure 6). Panels were assigned one of three thicknesses, either 45, 35 or 25mm. This value determines the thickness of the bottom left side of the diamond shape and reduces by 10mm across the face of the panel towards the top right side. This assignment uses a region based approach that includes a controlled random variation. Lastly, each panel is assigned one of six fluted milling patterns depending on its thickness (Figure 7).

A single panel takes approximately 30 minutes to pack into a mould. All panels were made over 7 days by a group of 15 people. During the casting process, a perforated metal connection is embedded within the back of each panel to secure it to the structure. Panels are then dried and milled.

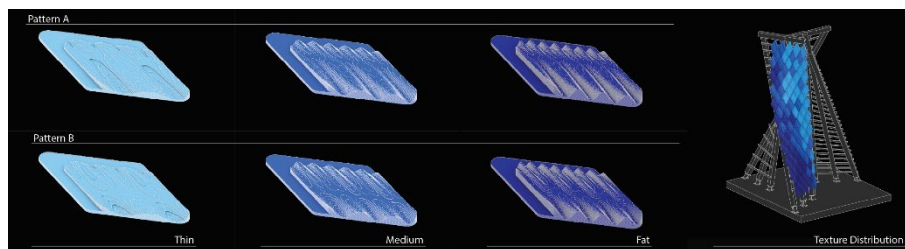


Figure 7. Segment of the façade design model showing assignments of thickness and fluting.

6. Sustainability Assessment

Key impacts calculated for the panel are presented in Table 1. They demonstrate a reduced footprint for the assessed panels compared to similar conventional building products. The panel presents amongst the lowest carbon emissions both in similar

panels and in construction products more largely. While it is not carbon-negative, as land bio-based products can be, it features lower emissions than almost all others (Munch-Petersen et al 2022).

Table 1. Life-Cycle Assessment results

Impact category	Reference unit	Result
Fossil resource scarcity	kg oil eq	7.29E+00
Freshwater ecotoxicity	kg 1,4-DCB	5.11E-05
Freshwater eutrophication	kg P eq	-4.6E-07
Global warming	kg CO ₂ eq	5.85E-01
Marine ecotoxicity	kg 1,4-DCB	8.80E-05
Marine eutrophication	kg N eq	-1.56E-01
Terrestrial acidification	kg SO ₂ eq	1.32E-03
Terrestrial ecotoxicity	kg 1,4-DCB	2.24E-01
Water consumption	m ³	2.37E-02

While carbon emissions associated with the panel are low (comparable to an unfired clay brick), it is also notable that the marine eutrophication potential associated with it is negative. This reflects the ability of mussel shells to absorb a range of nutrients from the water as they grow - carbon but more importantly potassium, phosphate and nitrogen (Plesner et al 2015). Mussel shells have been a focus of attention in the blue industries precisely for this ability, rendering them capable of cleaning ecosystems while cultivated. A negative marine eutrophication potential has not been observed in other construction materials, demonstrating the novel regenerative ability of this material system.

A sensitivity study has been conducted by breaking down the results, evaluating the differences in impacts if the mussel shells were sourced as a waste product of the food industry rather than cultivated for primary use in the panel. Gathered shells are not considered given the ongoing scientific debate on the impacts of their harvest method, which are unclear and therefore difficult to integrate. The sensitivity study follows the EN15804 guidelines for carbon allocation and applying them to the nutrients intake allocation: the cultivated shell is a single output product with no need for allocation, while the waste shell allocates 100% of the intake to the primary product (mussel meat). In the case of a waste shell, the GWP impact would be 24% lower (3.9E-01 kg CO₂ eq) than the assessed cultivated shell, and the marine eutrophication potential would raise from -1.56E-01 to 2.0E-02 kg of CO₂. The regenerative action on ecosystems would be lost to the accounting. This advocates for an extension of regenerative potentials accounted for in crediting systems with an allocation strategy expanding beyond carbon to incorporate ecological remediation, as well as for considering the advantages of extending mussel shell cultivation beyond blue food industries.

6. Discussion

The research and results detailed in this paper point towards the potential for blue bio-composites within cultivated construction. Developed as an adaptive material system, the ambition for this bio composite is to allow for local, regionally specific recipes to be developed. Properties, specifically the visual expression of the mussel-shell biocomposite, have been shown to be inherently driven by the combination of the constituent materials. While only very limited testing of other architectural properties is reported here, assessing one version of the recipe, it can be assumed that this recipe/property relationship extends to mechanical performance and response to fire, and perhaps to moisture absorption. Rather than this variability being a limitation, the paper demonstrates how computational design, grading strategies, and fabrication workflows facilitate architectural compositional strategies that can leverage it while maintaining fabrication feasibility and functional performance.

Life-cycle assessment results indicate that the mussel-shell composite exhibits low embodied carbon and, critically, a negative marine eutrophication potential when mussel cultivation is included within system boundaries. This finding is significant because it challenges prevailing approaches to material assessment in architecture, which typically account only for emissions and resource depletion, rather than ecological regeneration. By showing that material production can actively contribute to the mitigation of eutrophication through nutrient removal and habitat formation, the research develops understanding of materials as renewable ecological agents rather than scarce environmental burdens. This reframing has implications for how architectural materials are valued and compared within sustainability frameworks.

The full-scale demonstrator provides evidence that the material system can operate as architectural cladding. This does not claim immediate readiness for industrial mass production, but instead demonstrates a viable pathway for scaling out through the combination of an adaptive material system and the valorisation of an inter-sector waste as an alternative to conventional industrial scaling logics. Further development would need to analyse these opportunities locally: eelgrass and mussel shell are in some areas abundant on European coastlines, are cultivated for food using techniques that have greater or lesser environmental impact, and are even an invasive species in some locations. This creates an existing network of origin locations for cascaded ingredients, opening perspectives for larger scale production.

7. Conclusion

This paper has described a novel bio-composite and its application as a full-scale façade cladding in a built demonstrator. The paper has detailed the digital design pipeline and hybrid fabrication process, described the material and environmental performance, and discussed the implications of localised material availability and variability as it effects material and environmental performance and architectural design thinking. Beyond the feasibility demonstration of a blue biomass composite material, the research opens up consideration of how the geographic origins and processing flows can be considered within compositional and sustainability approaches. Outlooks include 1) further performance testing of the material system to extend understanding of how performance is impacted by variability present in the shells themselves, and 2)

investigation of alternative manufacturing methods for the material systems, as the mixture is versatile and could be suitable not only for casting, but also for an extended range of additive manufacturing and forming techniques.

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