On Light and Matter: Structural Optics of Biomaterials

by

Laure Nolte

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Dalhousie University is located in Mi'kmaq'i,
the ancestral and unceded territory of the Mi'kmaq.
We are all Treaty people.

For Joan, Brenda and Pauline,

my guiding lights.

Contents

Abstract

The wings of a morpho butterfly exhibit a dazzling display of crystalline blue that transforms with viewing angle. The optical properties demonstrated by this improbable blue are produced not by pigment but as a function of material and structure. This phenomenon, known as structural colouration, highlights a direct relationship between light and matter.

Biomaterials, like the carrageenan found in macroalgae and calcium carbonate found in mollusc shells, have an impressive array of mechanical and optical properties but have not been explored to their full potential within the domain of design. This research is comprised of three phases: ecosystem scale research into material flows and biogenic waste streams, biomaterial development and fabrication, and finally the culmination of research in an exhibition proposal of light assembled with biological materials generated by the sea, with the aim to demonstrate symbiotic relationships between structure, matter and optics at the human scale.

Acknowledgements

I would like to thank my supervisor James Forren for his support throughout my master’s degree and for encouraging me to ‘stay with the trouble’ when I felt challenged by my own vision.

I would also like to thank my colleagues and co-conspirators at Material, Body and Environment lab. My experience at MBE has had a profound influence on the shape and direction of my future in architecture.

I would also like to thank my advisor, Sarah Bonnemaison, for her discerning wisdom and support throughout my thesis.

And to my advisor Hugh MacIntyre, whose belief in the ‘unreasonable’ people of this world (George Bernard Shaw) has offered me a rare educational experience at the intersection of oceanography and architecture.

Chapter 1: Introduction

Prologue

The following thesis documents a journey rather than a project. Like most consequential journeys, I ended up where I least expected. Beginning with a biologically informed study inspired by material cycles of the Ocean, and through material-based experiments and iterations I found myself drawing from Bauhaus based principles of visual perception. Modernism, the paradigm I sought to challenge through material driven design, offered me a proto language with which to read the biomaterials I was working with. It was through a close study of Josef Albers book *Interactions of Colour* that I began to discern the nuanced optical properties in the materials I was working with. In other words, it was through a practice of "seeing" guided by Albers that these materials came to light and I honed a deeper vision in the process. As Albers summates in this text, "What counts here—first and last—is not so-called knowledge of so-called facts, but vision—seeing. Seeing here implies Schauen (as in Weltanschauung) and is coupled with fantasy, with imagination" (Albers 2013, 2). To Albers vision is both literal and metaphorical, it is material and it is phenomenal.

The Assembly of Light

The ephemeral power of light has long been revered by architects. This thesis emerges from the notion that material and microstructure are progenitors of the assembly of light at an architectural scale. The driving question behind this inquiry is how a multifaceted experience of light in architecture can be generated from a materials perspective in addition to a formal one.

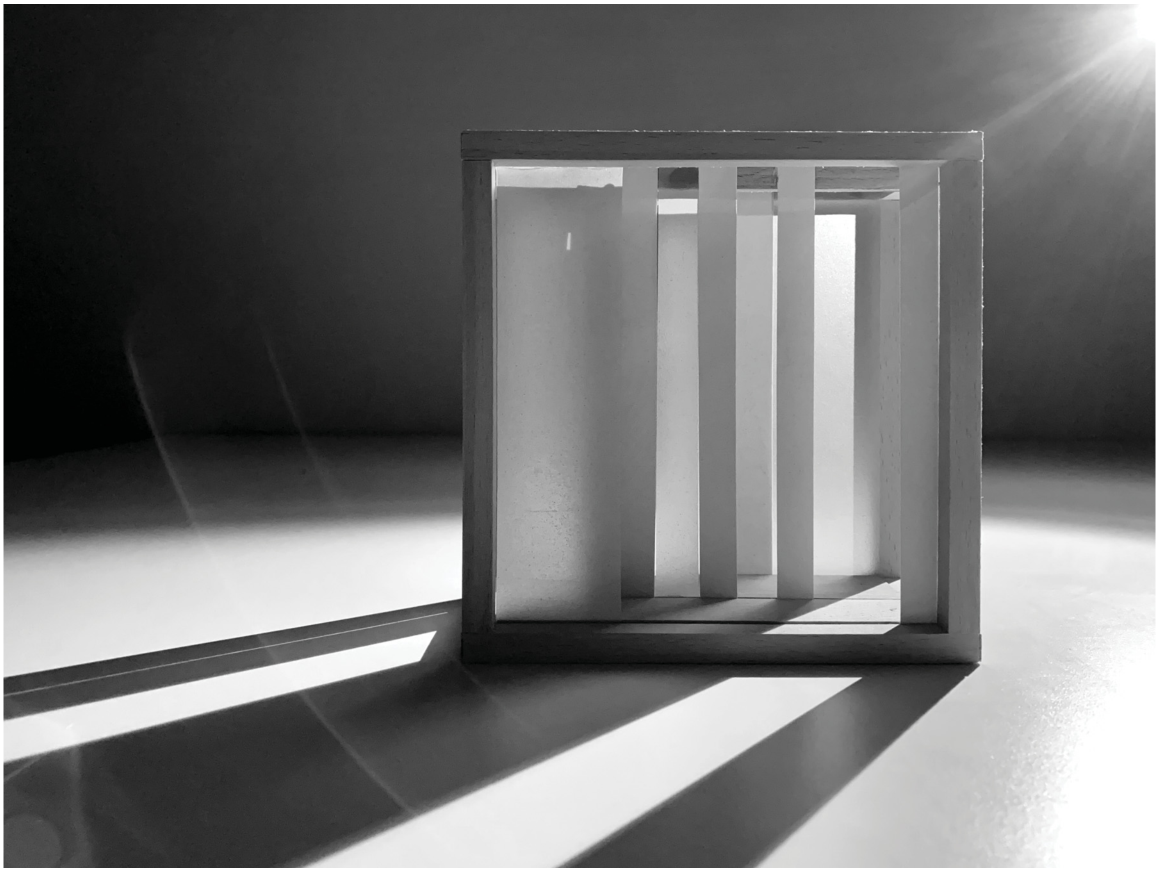
Diffraction patterns engaging light and water at Tangier Harbour, NS. 2021.

In nature, optical properties like iridescence and absorption are generated as a function of material and structure, thereby highlighting a direct relationship between light and matter. In addition, biological materials are in constant response to variations in the surrounding environment: light, temperature, and humidity. Given the significance of these entangled relationships for design, biomaterials, optical properties and environmental forces will be explored in tandem to generate form. The aim is to engage matter from the beginning of the design process by using contemporary methods to adapt physics-based principles to a microscale material composition generated from feedstocks that are in dialogue with a broader ecosystem scale context.

Informed by locally generated biomaterials and principles of visual perception, this thesis calls for expanding light's potential within architecture through designing across scales, from microstructural to architectural. Optical properties of biomaterials will be explored through the following approaches: by producing a gradient of material compositions in discrete components, through variation of heterogenous properties within a single membrane, and by constructing complementary and contrasting visual relationships in response to modern aesthetic theories. The design experiments will culminate in an exhibition of light assembled with biological materials generated by the sea, with the aim to demonstrate symbiotic relationships between structure, matter and optics at the human scale.

Material Cycles of the Ocean

We are standing on the precipice of a moment in time where the mass of human generated artifacts has superseded the mass of non-human generated biomass (Elhacham et al.



Biomaterial model light studies. 2022.

2020). One need not look far for a superior model. Biological systems, such as ocean's ecosystem, the mother of all biological life, offers a model for a material culture based on repeating cycles of life generation and transmutation. This contrasts the linear model ubiquitous in current construction practices, which follows a trajectory of extraction to material to product to waste and landfill.

The cyclical model may contrast current construction practices, but it is not new or without precedent in human cultures. Although Indigenous heritage is not the topic of this thesis, it is important to note that many Indigenous cultures throughout the world observe cyclical models of resource stewardship and engagement. For instance, Gregory Cajete, Tewa author of *Native Science*, suggests that from

Seaweed floating ashore at Tangier Harbour, NS. 2021.

an Indigenous perspective "how something is related and the nature of causality in a given natural context are foci of deep reflection. The ways in which aspects of nature are transformed through time and space demand the observation of subtle details that are the foundation of knowledge" (Cajete 2000, 66). Again, although Indigenous heritage is not the topic of this thesis, it is an ambition of this thesis to access a kind of "observation of subtle details" through actively and passively tuning in to the subtleties occurring at the boundaries of our perception. Such attunement is not dissimilar from the ambitions of Albers's exercises at the Bauhaus and Black Mountain College: a training of perception that was at once cultural, psychological, and part of a social ethic (Diaz 2014). In a time of climate crisis and ecological uncertainty, these touchstones of attunement can ground technological inquiry with perceptual insight.

A walk along the beach reveals the intricate intelligence inherent in Nature's material cycles. The beach itself is a hybrid of geological, biological, and anthropogenic cycles, with tiny flecks of sand interspersed with green glass, and shards of iridescent calcite shells of molluscs gently softened by the rhythm of the ocean. Light brings matter into the biological world through processes like photosynthesis and biomineralization. Fronds from nearby kelp beds washed up on the beach are in a state of visible transmutation. Microorganisms break down into constituent parts plant matter that is no longer performing cellular function. These nutrients will be washed back into the ocean to become new life forms. Over time, the building blocks of matter will make their way up through the trophic levels and the cycles will repeat.

Designing with Nature's Wisdom

We are only a few generations removed from a building culture that is primarily decomposable. It is not a stretch to imagine a built environment predicated on waste free methods of building. In addition to being fully decomposable, biological materials, or biomaterials, offer opportunities for alternate paradigms of design, like Material Ecology (Oxman 2010b), where material rather than form is the point of departure in the design process and matter can be computationally grown and fabricated through processes like additive manufacturing. Material-based design has implications to engage dynamic material behavior when properties at multiple scales work in tandem with shape formation.

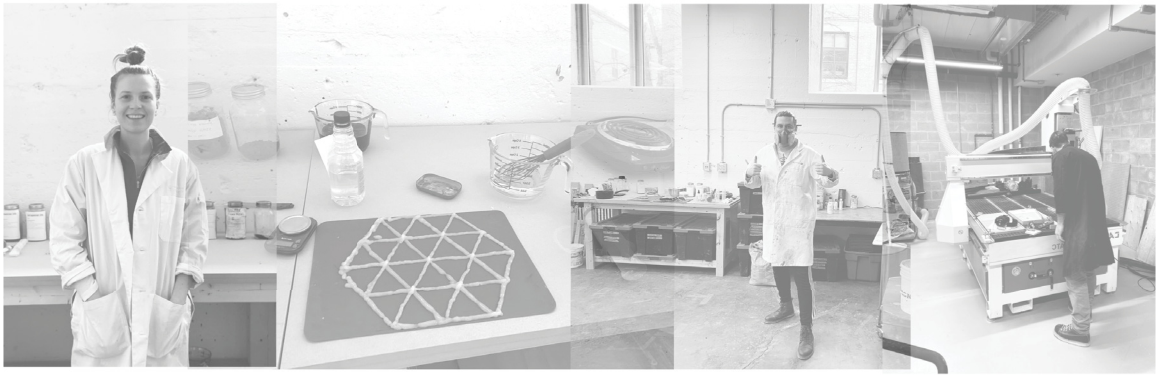
A common critique of contemporary architectural design, especially where computational design methods are at play, is that materials are subsidiary to form and often applied as an afterthought. As Oxman muses in "Material-based Design Computation", "the architects passionate search for

Baltee Island, Eastern Shore Islands Archipelago, NS. 2021.

form has prioritized formal expression and consequently deeply victimized environmental sustainability. A materials-based approach to design, potentially replacing this form syndrome with material sensibility, may be of significant impact in today's climate of environmental crisis" (Oxman 2010a, 73). This is not a new perspective, many architects including but not limited to Gaudi, Aalto, Otto, Candela, and Zumthor have wrestled with material agency over formal convention, but it is vital that a material awareness is at the forefront of inquiry as we face increasing uncertainty with anthropogenically induced ecosystem degradation.

The specification of globally distributed materials derived from environmentally damaging extractive practices like mining is embedded in the contemporary systems architects work within. Even seemingly natural materials like wood and mass timber, a frequent climate change solution in architecture, are primarily grown in synthetic plantations far removed from the heterogenous assemblage of a forest. Because the forest functions as a superorganism, the homogeneous nature of this plantation culture has erased forests' innate wisdom and communication channels which not only have direct implications on the material properties of the wood, but on the multispecies assemblages that find refuge in the woods. There is a wisdom to the way in which Nature generates materials and material properties.

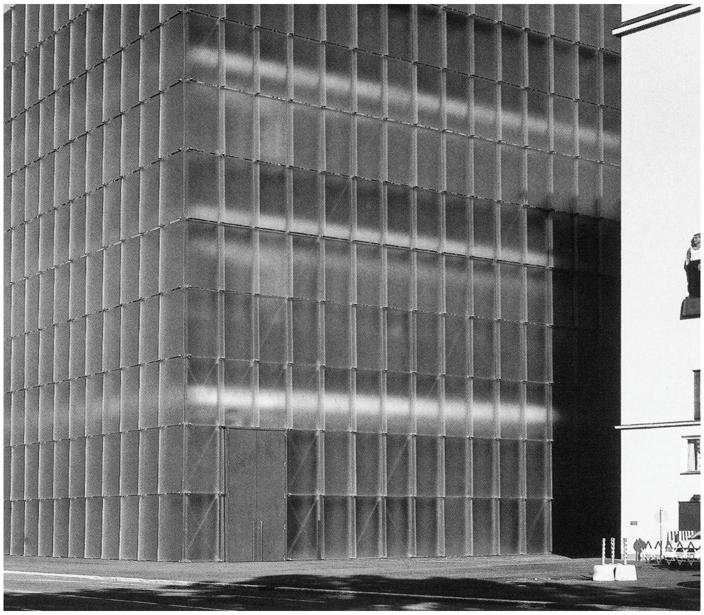
According to Gregory Cajete, "Western society continues to deny the spirit and intelligence of nature" (Cajete 2000). Every stage of the material cycle, from generation to decomposition, can be considered of vital importance to the emergent properties of materials, in addition to the health and biodiversity of the surrounding environment. When the designer primarily focuses on honing form through computational platforms biased towards geometry, homogenized materials like steel, concrete, or engineered timber are often utilized to perform standardized, single-



Hybrid research environments like Material, Body and Environment Lab at Dalhousie University enable a design / lab environment where material inquiry is integral to the design process. 2021.

use functions, like structural frame. In contrast, Oxman has claimed that “natural material systems and structures are capable of changing their properties, shape, colour and load paths to account for varying structural and environmental constraints as well as to handle damage and promote repair” (Oxman 2010a, 44). Form in nature, unlike form in conventional building practice, is uniquely tuned to have multifunctional capabilities and heterogeneous material properties.

A challenge this thesis needed to confront is how might this heterogeneity be encountered and worked with in design. For instance, as will be shown later, the author engaged in deep material study and inquiry while developing materials from marine feedstocks. While Oxman’s discourse points towards non-linear formal organizations (such as additively manufactured folding surfaces mimicking organic cellular organized structures like the dragonfly wing). This thesis challenges, in part, this paradigm to ask if the heterogeneity of biomaterials can be richly encountered within linear formal organizations that are a part of conventional



Bregenz Art Museum. (Gigon and Zumthor 1997) construction vocabulary. Do biomaterial projects need to look like dragonfly wings, or can they be utilized as systems to rethink conventional panelized construction practices?

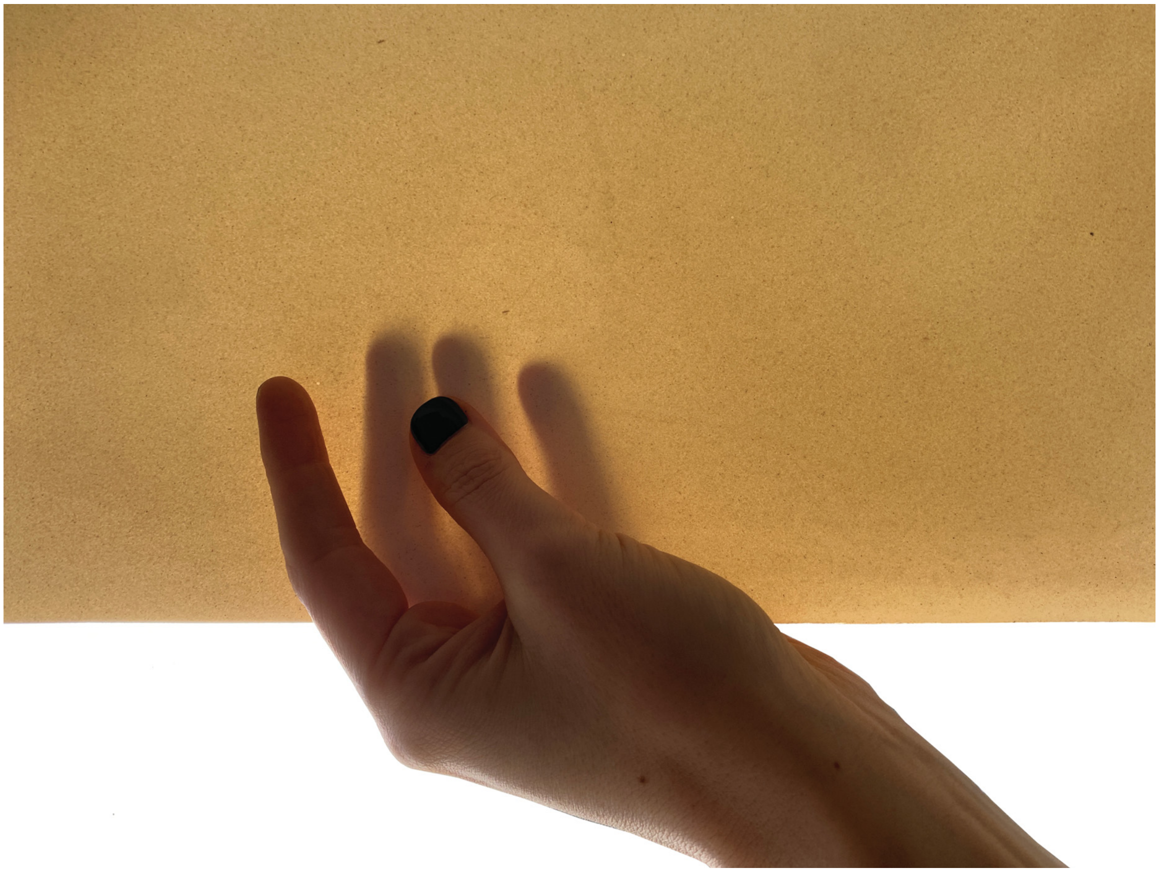
Author with 1000-year-old Sitka Spruce in Olympic National Forest, Washington. 2017.

Trying to design without acknowledging that the materials we are designing with have their own set of behaviors, responses and agency will always result in limited outcomes, and limits the creative process itself. When we begin to recognize matter as being spirited, a shift in perception occurs, and the designer can actively co-create with materials.

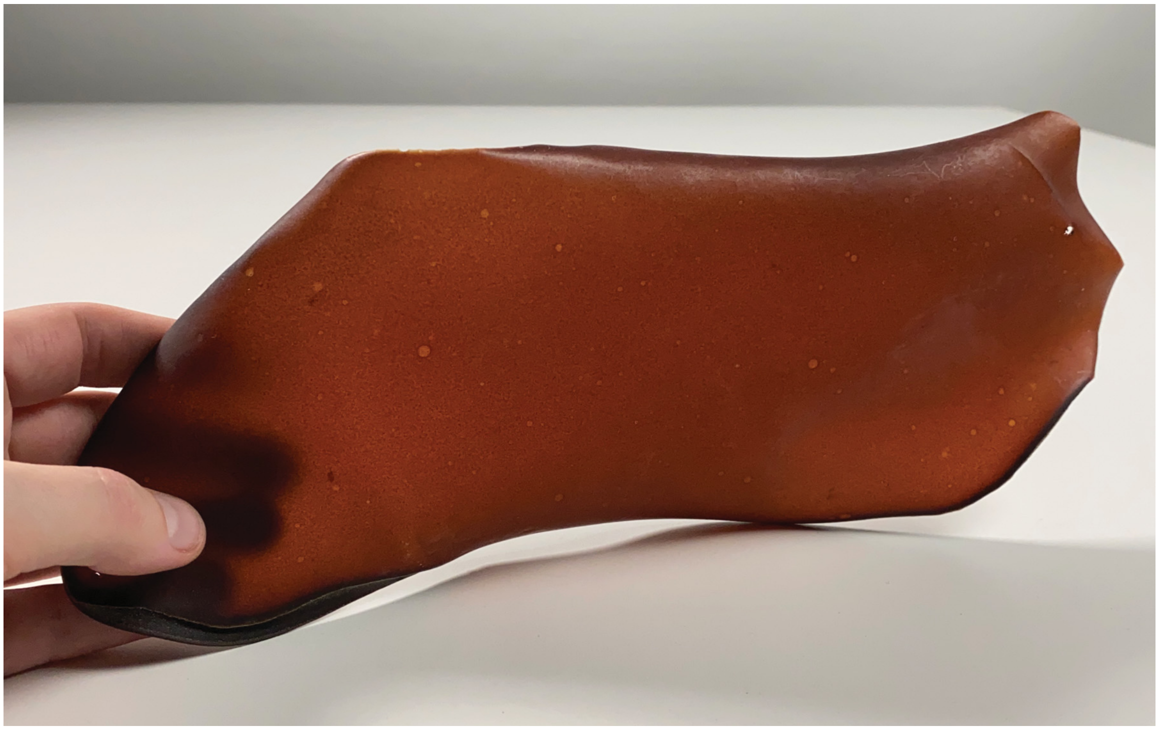
At the same time, we build within a hybridized condition where we are humans and natural agents, and we have established social codes, conventions, and customs that form a constellation of their own, even if they are not derived from an earth-centered cosmology. The thesis is as much about how we work within this hybridized context as much as it is about trying to radically reshape the industry. Could a path towards reshaping happen through hybridity rather than extreme technological transformation? This thesis explores this hybrid space: although some material fabrication was explored using technologies like Computerized Numerical Control (CNC), most of the biomaterial fabrication was done using low tech approaches like casting and molding.

Fossilized tension wood in cross section. (Wheeler n.d. as cited in Groover 2016)

Working with biomaterials can engage processes like growth and decay that challenge outmoded conventions of architecture rooted in the Industrial Revolution as Oxman demonstrates in her work. Further, working with responsive and spirited systems transforming through time and space offer opportunities for grounding a foundation of knowledge in an animated world (Abram 1996; Cajete 2000; Haraway 2016; Tsing et al. 2017).



Translucent carrageenan biomaterial sample. 2021.



Avocado seed dye biomaterial sample. 2020.

Close up of materially induced warping patterns in carrageenan calcium carbonate membrane.

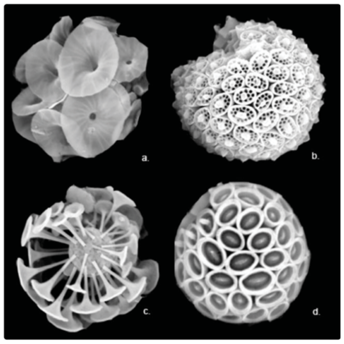
Close up of translucency and light interacting with warping patterns.

Chapter 2: Background

The material origins of this thesis are both ancient and futuristic. From a chemical standpoint, these constituent parts have had countless lives on timescales beyond comprehension. The following section will look at these components simultaneously like a chemist and an alchemist. Part of this process is knowing what outcomes can be controlled at what point to let material agency take the lead. This comes from an understanding that the materials are capable of phenomenal and unexpected possibilities when their rhythms and cycles are studied, understood, and respected, within the domain of architecture and beyond.

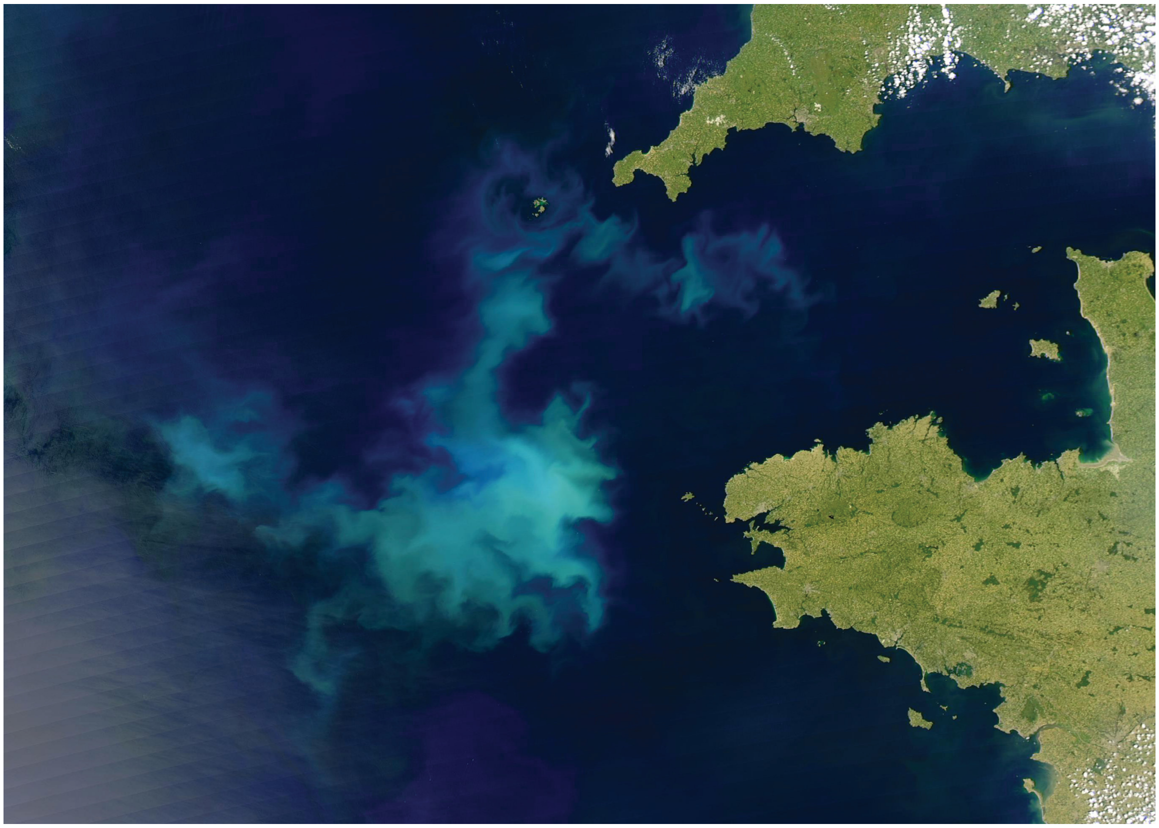
Red algae. (Haeckel et al. 2012)

The biological materials explored in this thesis are composed of matter derived largely from living or once living marine organisms. Biological materials are shaped by biological processes which often combine dissimilar properties, like strength or translucency, through their various incarnations. In the case of carrageenan, the origins of this material can be traced along the coasts of the North Atlantic. Chondrus crispus from which carrageenan is derived is generated through a process of photosynthesis. In other words, it is materialized by light. Calcium carbonate, a chemical compound found in many biological ceramics, can be biosynthesized by marine organisms such as molluscs, corals, sponges and coccolithophores.



Scanning Electron Microscope images of Coccolithophores. (Beaufort 2016)

Coccolithophores, a species of phytoplankton, are distinguished from other microalgae by their intricate biomineralized calcium carbonate discs. The calcite that composes these discs is an optically translucent material. The translucency of the calcite shell enables the coccolithophore to photosynthesize through their structure. Coccolithophores



Coccolithophore bloom from space shows the global significance of microscale marine organisms in the carbon cycle. (Descloitres 2004)

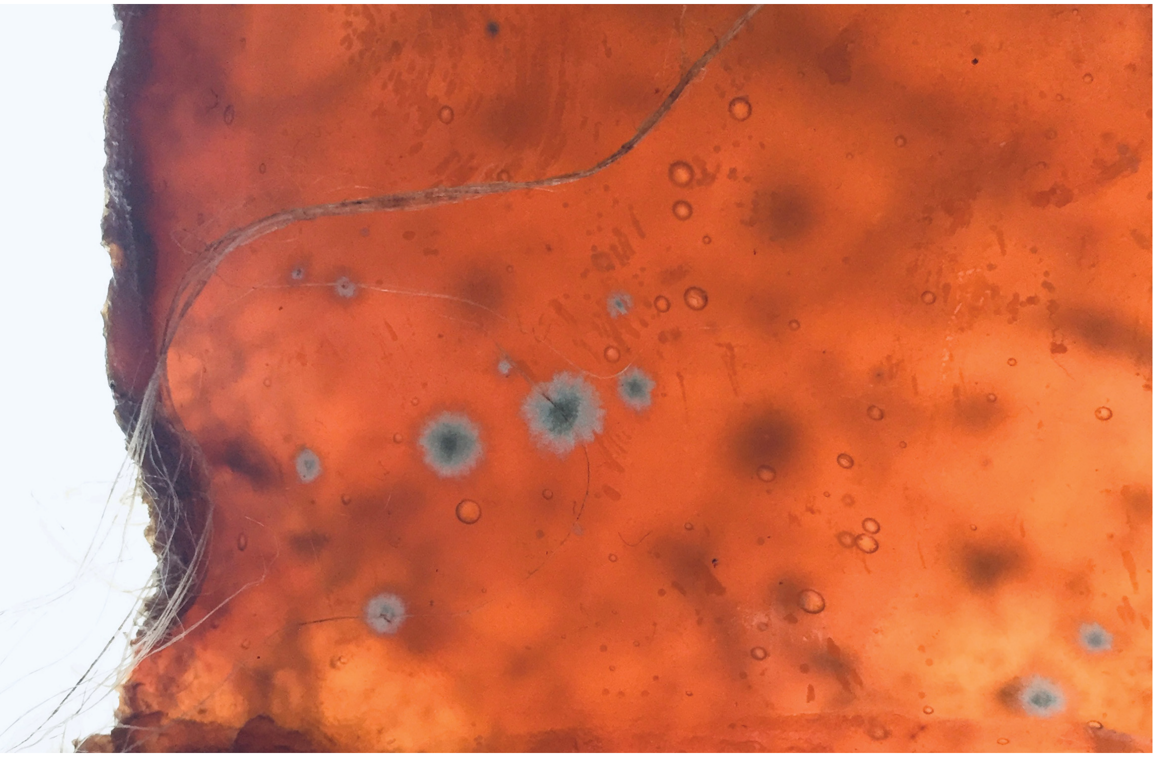
ability to produce energy from inside a structural shell is a fascinating adaptation with implications for the architectural scale. Imagine if our homes could produce their own energy and food. Additionally, the material that makes up this rigid shell is produced in ambient conditions, unlike the high temperatures and pressures used to generate conventional building materials like cement and steel.

Extending the understanding of architecture from floor, wall and roof to material, body and environment, questions will arise as materials are situated within their broader environmental context and subsequently in explorations carried out within the design lab environment. The aim is to draw forward a reading of “the porous and palimpsestic, biological and cultural, material and semiotic” nature of the

Material membrane showing tensile strength and translucency in its desiccated form.

material bodies of this thesis as they emerge and iterate through the design process (Neimanis 2017, 42).

An architectural reading immediately situates us within space time. The following design experiments generate membranes that can be read as linear, rhythmic, and cyclical and at the same time earthly; carnal, material. Andrea Ling’s thesis “Decay by Design, Design by Decay” embraces the temporal process of decomposition as a driver of design. In contrast to the life cycles of materials like concrete and plastics, which range from hundreds of years to thousands, Ling argues that the tendency for biomaterials rapidly change in relationship to environmental conditions form can be seen as a generative strength. The constant transformation of the biomaterials explored in this thesis demonstrate the animated nature of matter. In the



Colonization of fungi on biomaterial membrane. 2020.

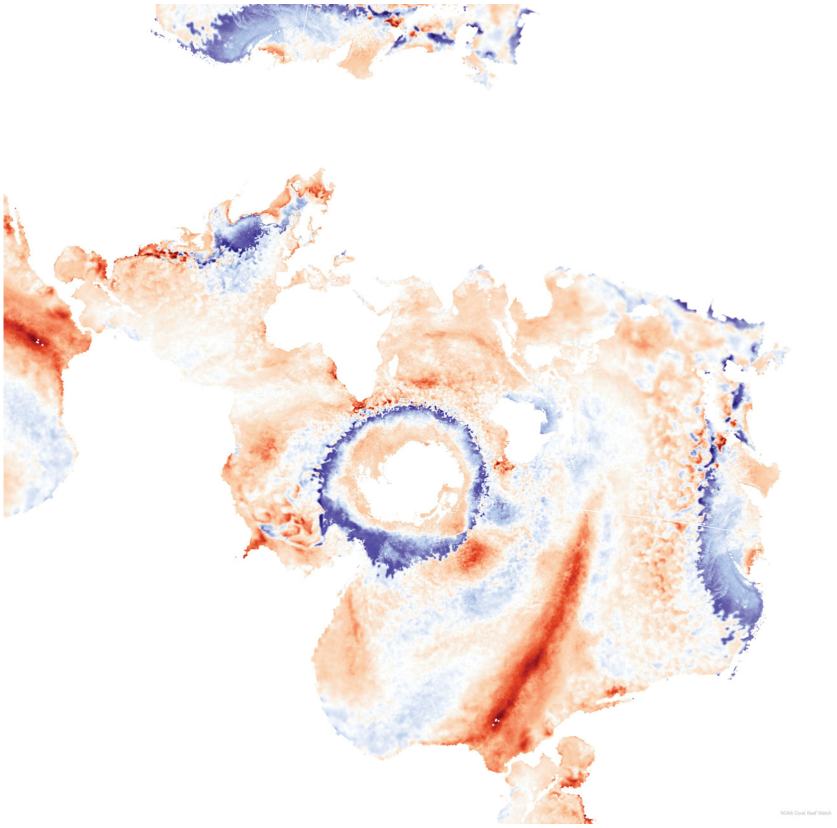
end: light, water, and heat, the very conditions that brought these materials into their current form are forces that will aid the dissolution of their chemistry back into constituent parts. The temporal understandings of the materials explored in this thesis and their inherent properties are situated within a dynamic context, therefore I aim to convey these artifacts, rather than objects, as ever-changing life processes in a design environment that seeks to embrace fragility, uncertainty, and decomposition.

Extractive Implications

This thesis works with biomaterial compositions derived from the material ecologies of the North Atlantic coast, such as seaweed and mollusc shells. Each of these biomaterials are engaged in cycles at both the local and global scale which will be discussed in the following section. It is important to first understand where these organisms came from and their larger roles within ecological and ecosystem relationships. Further, although not within the immediate scope of this thesis, the question of location raises an ethical question surrounding harvesting and extraction that the building and construction industry cannot continue to ignore, for reasons pertaining to resource depletion, environmental degradation but also who exactly these resources are being extracted from. Understanding how and where these materials are harvested or extracted and to what extent and where they are processed, can uncover ecosystem impacts that are not immediately visible, such as water usage, fertilizer runoff and social injustice. The environment will always render visible where impacts stemming from societal inequalities: race, gender and class are disproportionately experienced.

As the threads weaving together these matters of concern (Puig de la Bellacasa) are untangled the question of whether humans have a right to ‘use’ these materials in the first place arises. Further questions the work asks us to consider are: Without anthropomorphizing, how might consent be practiced with organisms themselves, or with the land and the sea? Is there reciprocity for the land, or sea or organisms in this exchange, or is it purely extractive, benefiting only the capitalist driven human realm? How, where and when can gratitude be practiced in this exchange? What are the mechanisms or methods through which these larger questions can be asked and assessed?

Additionally, as we are in a time of rapid ecosystem change, there are environmental and ecological changes taking place at the local scale and the global scale that might impact the organism’s fitness in the future. *Chondrus crispus*, like many other macroalgae, will be rendered vulnerable



Global sea surface temperature rendered in Spilhaus projection demonstrating the interconnected nature of all of earth’s oceans. (Base layers from Naval Oceanographic Office 2019 GIS data)

with increasing ocean temperatures and rising sea levels. Ocean acidification is disrupting calcium carbonate synthesizing organisms’ ability to produce shells. Without their architectures, they are exposed to turbulent conditions and vulnerable to predators. These questions exist on an enormous scale, and many do not have clear answers. Without seeking solutionism, these questions linger in their power, untied and unruly.

Biomaterial Origins

Water

The defining feature of our planet is water, it shapes everything on earth. Unsurprisingly it plays a major role in the materials in this section, in generation and formation.

Earthrise. (Anders 1968)

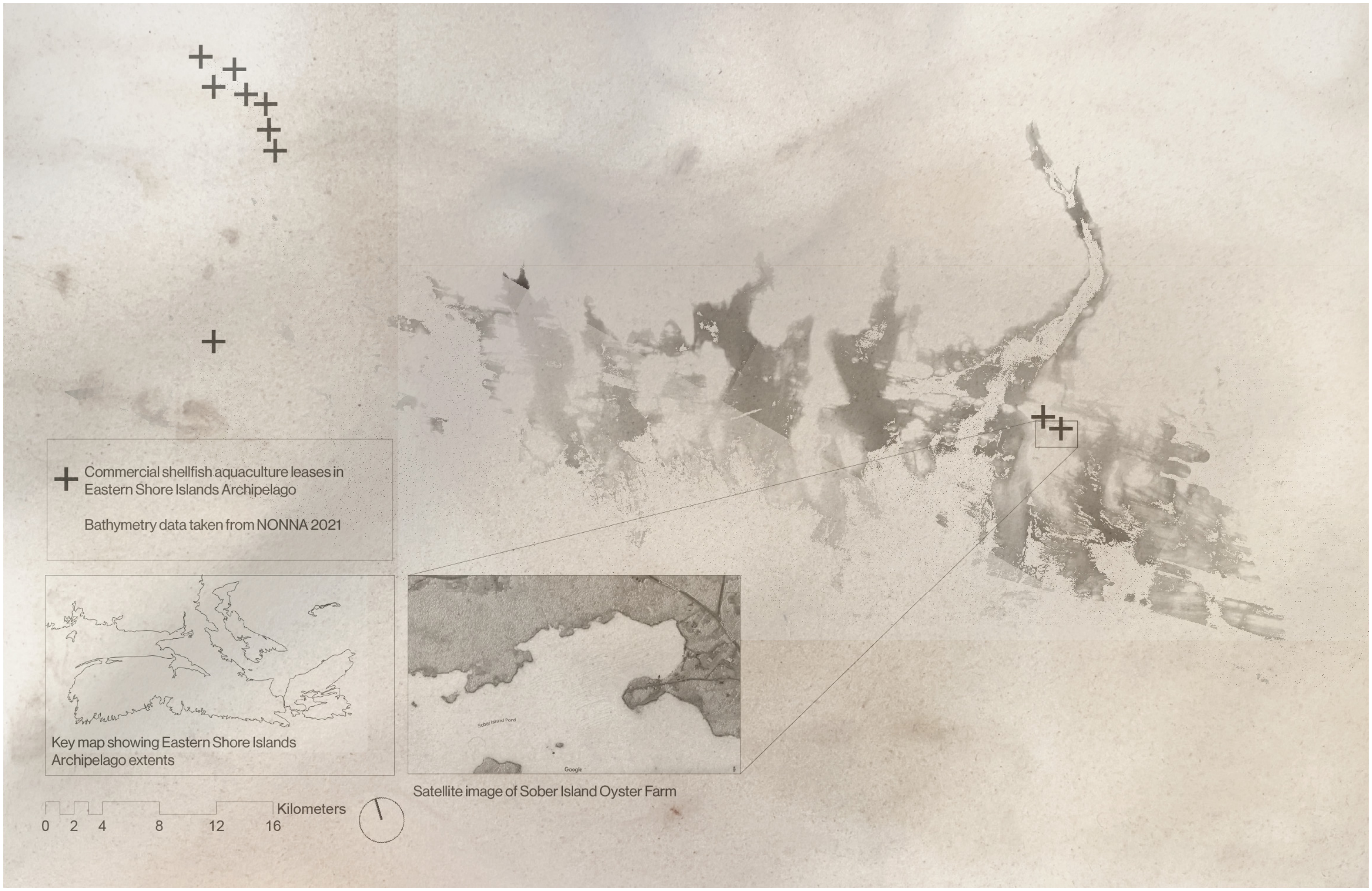
Both *Chondrus crispus* and calcium carbonate are involved in ocean dynamics at global scales. The generation of these materials could not occur without water (and light). As well, the formation of the material membranes within the lab environment relies on water, first to hydrate the carrageenan into a solution. After the membrane has been poured, as water moves out of the membrane it gains structural rigidity with desiccation. Further, as will be explored in the following section, the material properties of the membranes change depending on the relative humidity of the environment they are held in. Thus, the membranes result from their many relationships to water.

Calcium Carbonate

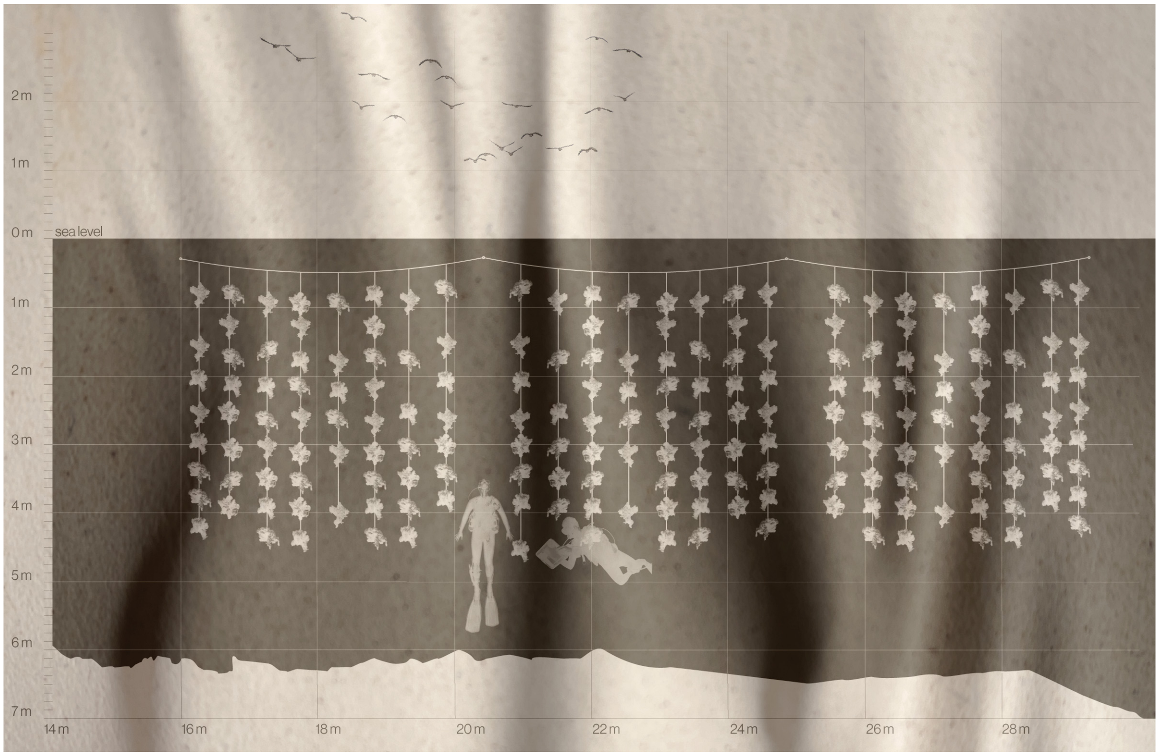
Calcium carbonate is in the realm of biological ceramics and can be found in organic materials from birds' eggs, teeth, sponge spicules, crustaceans to molluscs. All these materials have varying material properties and strengths, which can largely be attributed to the way in which the calcite crystals grow and form. According to Julien Vincent, while “animals and plants are able to manipulate the mineral phase in ceramic composites, chemists are still posing the question: How?” (Vincent 1990, 165). Biological ceramics, in many circumstances, are far superior to the ceramic materials we have been able to make as humans. Yet, biological ceramics are synthesized at ambient temperatures. The primary downside to this class of organic materials is the fact that the protein tends to denature at 60 degrees Celsius (Vincent 1990, 165).

Calcium carbonate is the most abundant chemical composition in the shells of marine organisms like oysters and mussels. In the geographic context of the coastal North Atlantic, shellfish aquaculture is a growing industry. While oysters and mussels are considered a delicacy, their shells are not, and are frequently disposed of. There is significant opportunity to tap into the waste streams of local aquaculture industry to turn the constituents from these shells from waste into architectural materials. This is not a new practice, examples of a material culture based on tabby concrete (a mixture of lime generated from oyster shells, water sand and broken oyster shells) and lime mortars are scattered along the Atlantic coast from Florida to Nova Scotia. Calcium carbonate was chosen as an additive in the following material experiments for two reasons: firstly, for its relative abundance in the aquaculture waste streams of the Nova Scotian geographic context, and secondly for its ability to significantly increase the strength and rigidity of the optical membrane.

Mussel and oyster shells.



Map showing commercial shellfish aquaculture leases in the Eastern Shore Island Archipelago. (Bathymetry data from Canadian Hydrographic Service Non-Navigational 2020)

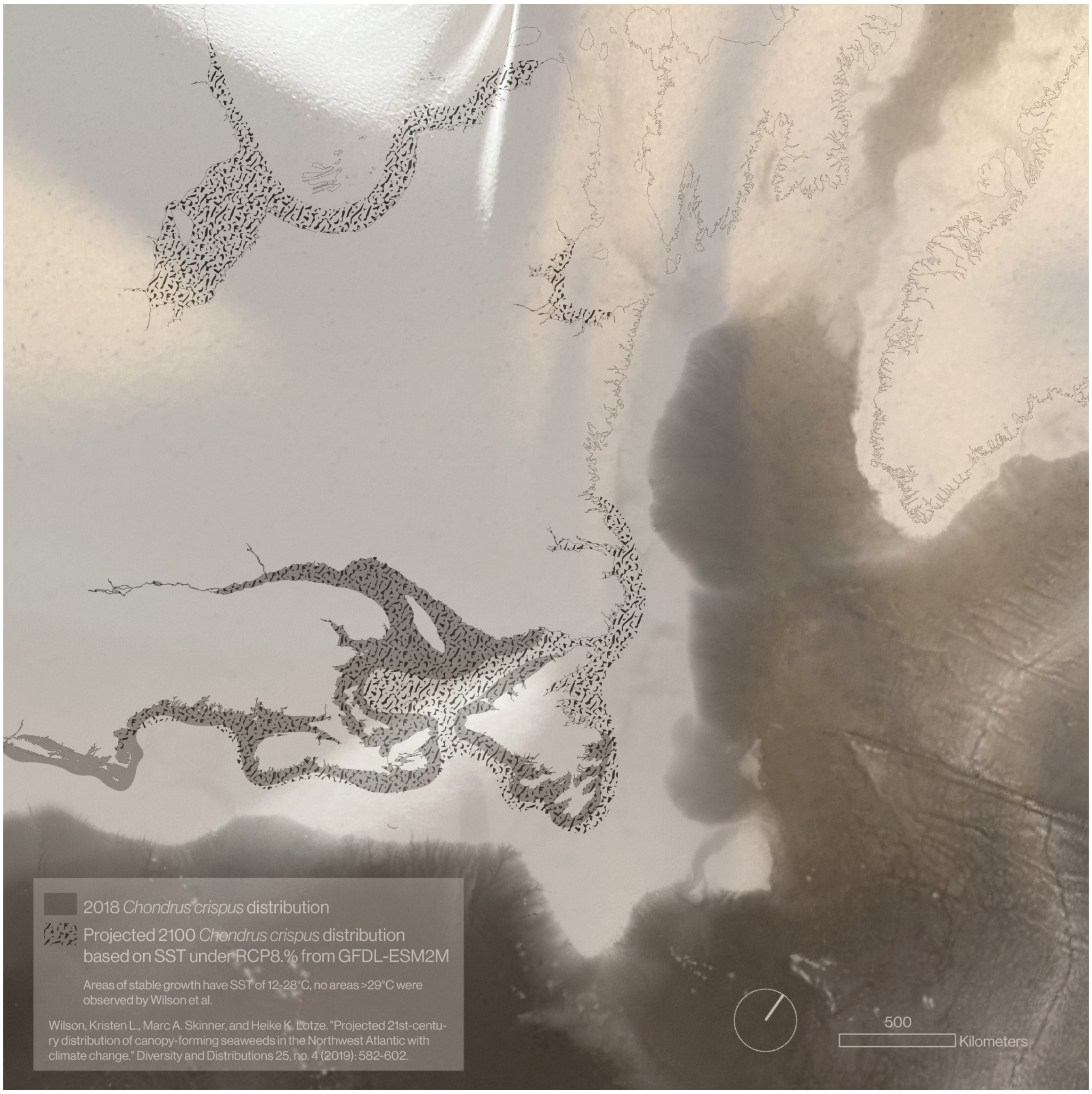


Section drawing of a typical oyster farm.

Carrageenan

Carageenan iota, an extract from the edible seaweed *Chondrus crispus* (common name, Irish Moss), is used as the base biopolymer in these compositions. It is a robust, translucent biopolymer that provides a flexible matrix for additives. *C. crispus* grows throughout the North Atlantic and is the primary source of carrageenan in Canada. Its growth varies between seasons and in different areas and is determined by biomass density, water temperature, solar radiation, and nutrient availability (Sharp et al. 2008). Irish Moss is typically wildcrafted manually using hand rakes and single crew skiffs.

Irish Moss beds are found in the lowest part of the intertidal and shallow subtidal zones, making it accessible for harvesting only 4 hours per day during the lowest tide

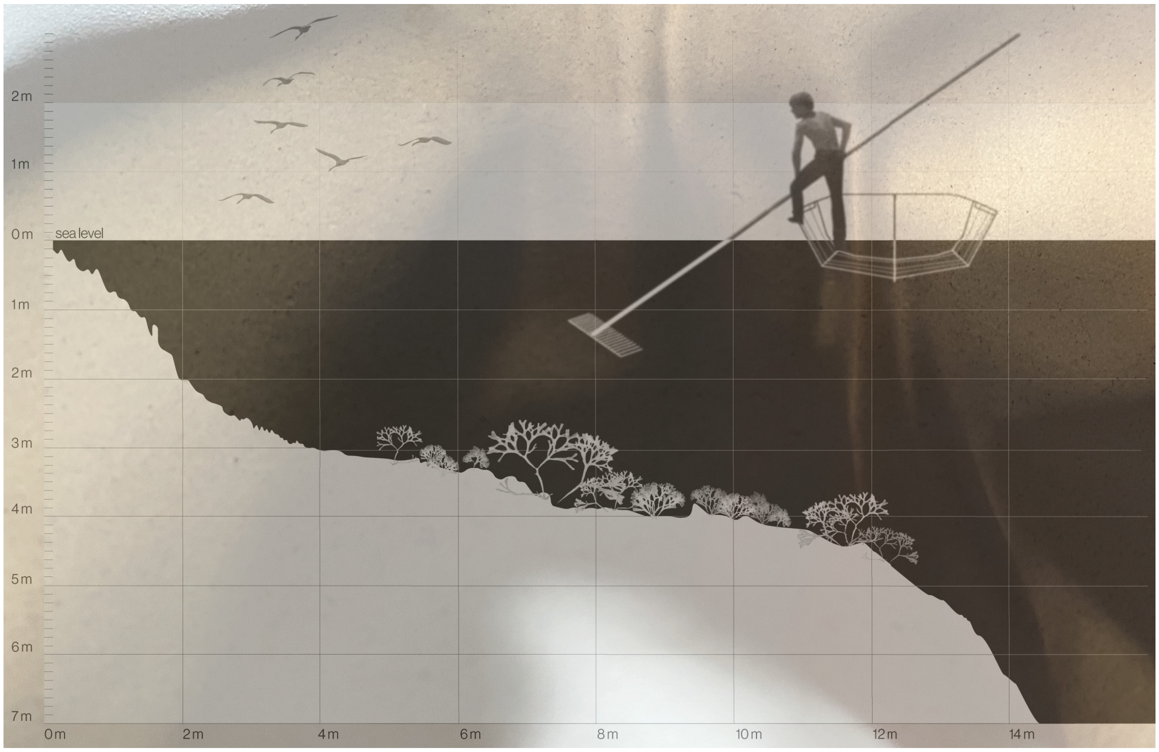


Wilson, Kristen L., Marc A. Skinner, and Heike K. Lotze. "Projected 21st-century distribution of canopy-forming seaweeds in the Northwest Atlantic with climate change." Diversity and Distributions 25, no. 4 (2019): 582-602.

Current (2019) and projected (2100) distribution of *Chondrus crispus* along Atlantic coast of North America. Bathymytry data from NASA. (Distribution data from Wilson, Skinner and Lotze 2019)

Chondrus crispus frond from Tor Bay. 2021.

series of the month. The rake used for hand harvesting is a culling instrument with spacing of 5mm which removes only the largest fronds leaving behind 80 to 90 % of the fronds. These understory fronds are then exposed to light and will have enhanced growth rates (Sharp et al. 2008). While Irish Moss grows abundantly in the wild, it can also



Section drawing of a typical *Chondrus crispus* bed.

be cultivated or farmed. Farming seaweed does not require fertilizer, pesticides, or nutrients like terrestrial farming, as ocean currents are constantly cycling nutrients. Farming can also be deployed as a bioremediation effort in polluted water ways as the algae adsorb heavy metals and excess nutrients (Arumugam et al. 2018). According to Sharp et al, the amount of regeneratively harvested Irish Moss landings in Nova Scotia is in the range of 1500 tonnes of material per year.

Chapter 3: Methodology

Overall Study Design

The following quote by Oxman suggests that, “Prior to the Industrial Revolution, hand production methods were abundant. Craft defined everything. The craftsman had an almost phenomenological knowledge of materials and intuited how to vary their properties according to their structural and environmental characteristics.” Taking a cue from Oxman’s observations of material relationships in craft, understanding material behavior and intuiting how to work with environmental uncertainty through constant fabrication became a driving force for the design development demonstrated in these experiments.

Notes on Material Compositions


Calcium carbonate.

Given that biomaterials are highly responsive to environmental stimuli, there are many variables that can affect the physical properties of the biopolymer membranes. When harnessed, many of these variables can leverage reciprocal relationships with material and designer to generate a range of outcomes. For example, increasing humidity in the membrane’s environment can enhance its flexibility and malleability, rendering it workable for a period of time, before it returns to a rigid state. Too much humidity and the membrane may start to disintegrate.


Carrageenan iota.

Typically, manufactured architectural materials are assumed to be static, maintaining their produced form. Materials produced from biological agents are in constant flux. This provides the opportunity for the inherent uncertainty of working with materials to be generative to the design process rather than limiting. To take advantage of these potentials requires precision and agility while working with the materials (Ling 2018). The following mixing protocol is intended as an aide towards this end.

Mixing Protocol

The following protocol can be used to produce 8 x 10" carrageenan/calcium carbonate sheets in varying thickness and containing between 0 to 8% calcium carbonate by volume. This protocol was developed over the course of several months and was used for the studies discussed in Chapter 5 and Chapter 6. This recipe was adapted from Materiom's open source material archive.

Required equipment:

Glass jars

150mL syringe

Mixing protocol process: hydrating carrageenan and calcium carbonate with water.

Hot plate or stirring hot plate

Stir stick

Laser cut formwork made from 1/8” Baltic birch

Silicone mat

Duct tape

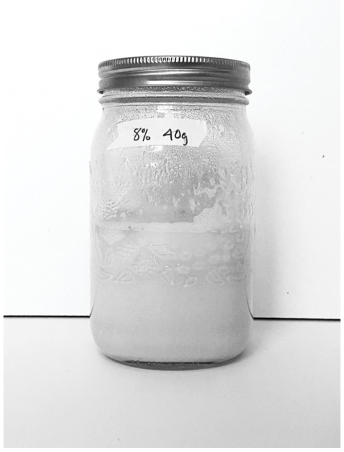
Material ingredients:

Water

Carrageenan iota

Calcium carbonate

Glycerine



Hydrating carrageenan and calcium carbonate with water.

Heating solution in water bath.

Steps:

01 Hydrate a 4% w/v (weight/volume) solution of carrageenan iota in water is hydrated at least 24 hours in advance of pouring or printing. If calcium carbonate will be added to the mix it is also incorporated at this stage at a w/v ratio between 0-8%.

02 Prepare the Baltic birch formwork in advance of heating the solution by taping onto silicone mat on level surface.

03 Heat the carrageenan/calcium carbonate solution in a closed container in a water bath to above 70°C and maintain this temperature while stirring for a minimum of five minutes. This constant temperature enables the carrageenan to crosslink which produces tensile strength in the final membrane. Glycerine is added as a plasticizer at this stage

Pouring solution into formwork.

Membranes drying in formwork.

in a ratio of 1 part glycerine to 100 parts water. The amount can be omitted or increased to 2mL depending on desired flexibility. More glycerine will result in more flexibility, too much while result in a gummy membrane. The solution will thicken when it is ready to be cast.

04 Pour the heated solution into a syringe vessel for printing or into a mould for casting. The temperature at which it is poured can be varied to either increase or decrease flowability, for example the warmer the solution is the less viscous it is. Below 50°C the solution will begin to solidify.

05 Leave the solution to dry (or desiccate) for several days at room temperature (between 15 and 30°C, with 20 to 60% relative humidity). Several factors will affect the drying time: membrane thickness (thicker will take longer); membrane additives (such as calcium carbonate, biochar, cellulose) will decrease drying time; relative humidity (RH) (higher humidity will take longer), room temperature (cooler temperature will take longer), and formwork material composition (more porous materials will decrease drying time. When the material is fully desiccated it can be carefully removed from formwork.

Chapter 4: Material Analysis

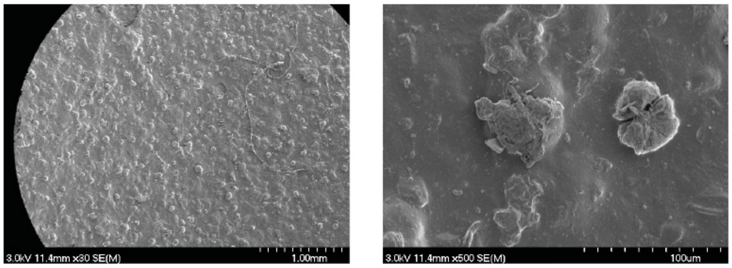
The material samples were analyzed in order to gain insight towards translating material properties into the domain of design. Optical properties were studied and analyzed under the supervision of Dr. Hugh MacIntyre in the Department of Oceanography at Dalhousie University. These values were quantified using a spectrophotometer and then qualified through generating an adaptation of Munsell colour chart. Micrographs of the materials at resolutions ranging from 30x - 1000x were taken by Patricia Scallion. Warping studies were carried out in order to understand if this material tendency could be programmed or tuned to a specific outcome. Finally, a humidity chamber was constructed to compare material behavior in relation to specific relative humidity values. The more insight gained into material behavior, the more questions arose. As well, it is interesting to note that while presented in distinct categories, most of these analyses are in dialogue with one another. For example, Scanning Electron Micrographs (SEM) revealed surface area conditions of the materials, which directly relate to spectral vs diffuse reflectance. I developed a deeper understanding of the physical phenomenon occurring at the human scale by analyzing surface conditions in high resolution and through conversations with my advisor Dr. Hugh MacIntyre, an expert in optics.

Analysis 1. Optical Density

From visual observation it appeared that calcium carbonate additives in the biomaterials increased the opacity of the membrane. To confirm this observation and to quantify the opacity of the material, light absorption (Optical Density), was measured using a spectrophotometer. Triplicates of

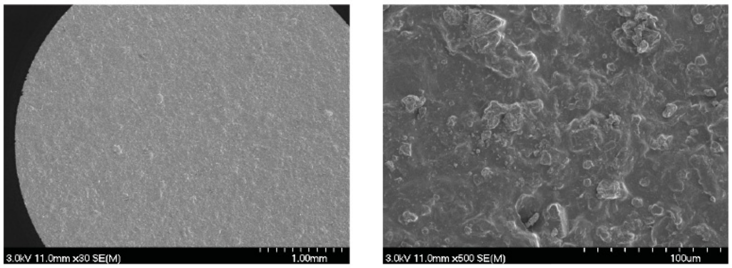
Value 00

Carageenan	04% (w/v)
Calcium carbonate	00% (w/v)
Glycerine	2.5% (v/v)
Water	93.5% (v/v)



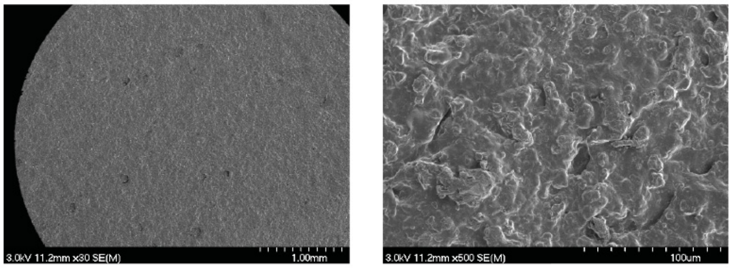
Value 01

Carageenan	04% (w/v)
Calcium carbonate	01% (w/v)
Glycerine	2.5% (v/v)
Water	93.5% (v/v)



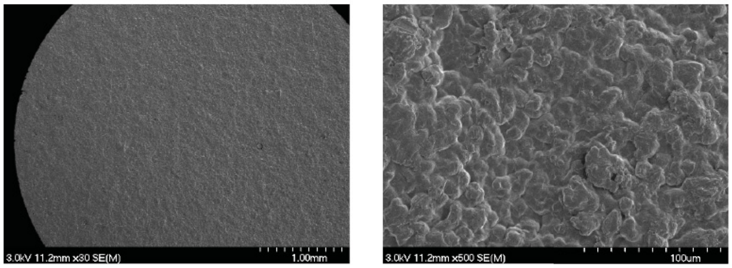
Value 02

Carageenan	04% (w/v)
Calcium carbonate	02% (w/v)
Glycerine	2.5% (v/v)
Water	93.5% (v/v)



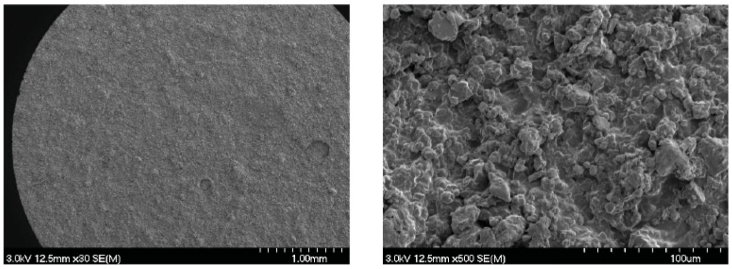
Value 04

Carageenan	04% (w/v)
Calcium carbonate	04% (w/v)
Glycerine	2.5% (v/v)
Water	93.5% (v/v)

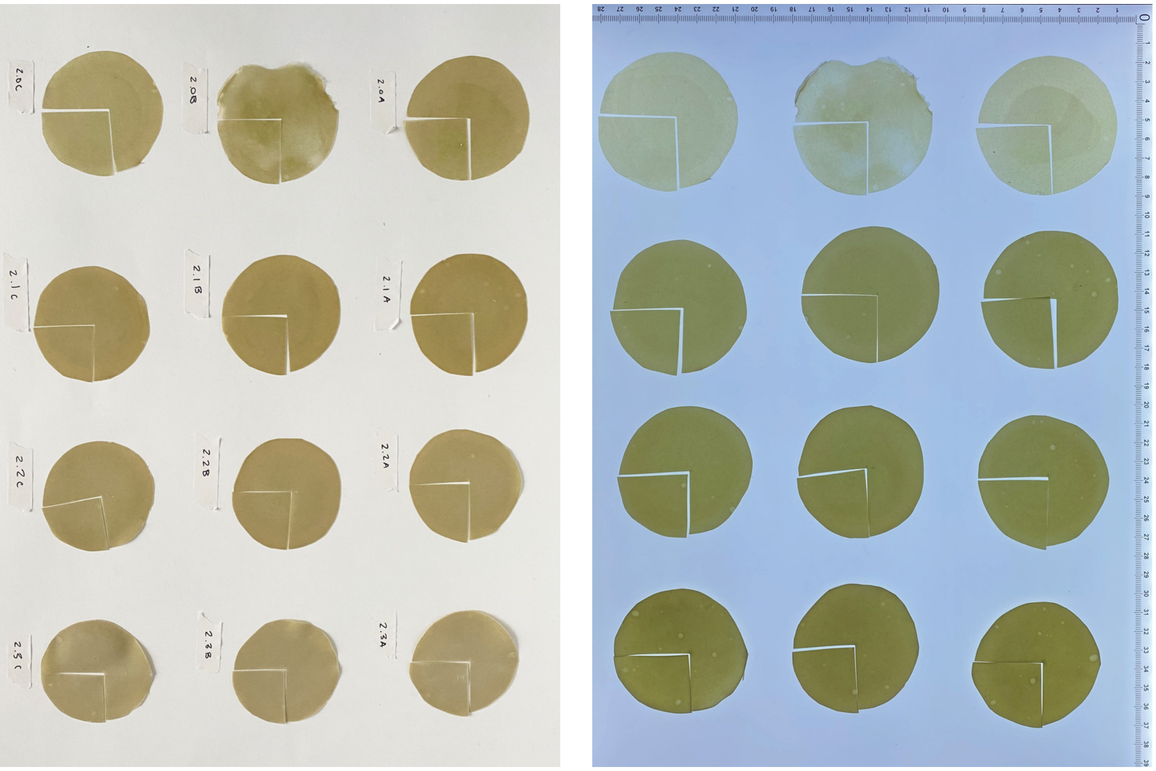


Value 08

Carageenan	04% (w/v)
Calcium carbonate	08% (w/v)
Glycerine	2.5% (v/v)
Water	93.5% (v/v)



Scanning Electron Micrographs at 1mm and 100um showing an increase of surface area of material samples in relationship to increasing ratio of calcium carbonate additive. SEM courtesy of Patricia Scallion.



Sample set that was used to measure optical density on the spectrophotometer. Left, natural light conditions, right photographed on a light table to see translucency. From top to bottom, control, 2%, 4%, 6% w/v calcium carbonate. See chart on following page for results.

biomaterial membrane samples were poured at 2%, 4% and 6% weight to volume (w/v) amounts with a control sample. The first set of scans (Absorption Spectra of Calcium Carbonate Additive and *Tetraselmis suecica* in Carrageenan iota Bioplastic Membrane) demonstrate an increase in optical density as a function of calcium carbonate. This can be seen as the curve increase as it moves towards the ultraviolet spectrum of the graph. These findings are in line with visual observations. By quantifying light absorption of the material, these optical properties can be programmed with precision to achieve specific outcomes. This has an array of implications for design, explored further in Chapter 5 and 6. It is important to note that calcium carbonate is not soluble in the carrageenan iota solution, rather it is suspended in the polysaccharide matrix. The increase in

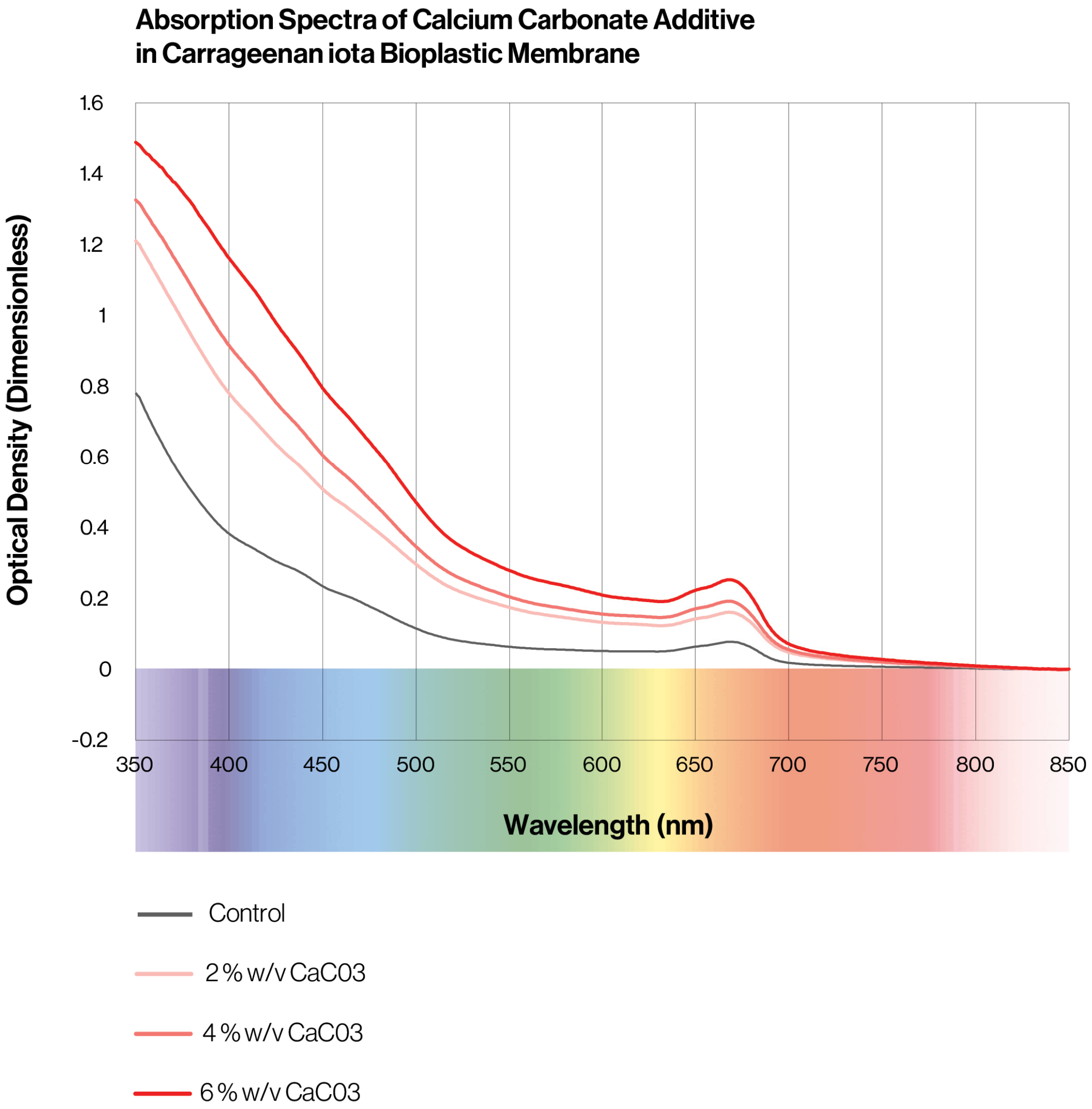


Figure shows a graph of increasing opacity in the CaCO3 material sample set.

opacity can be attributed to an increase of the density of calcium carbonate macromolecules which can be seen in the following SEM scans of five values of material: 0%, 1%, 2%, 4% and 8% w/v calcium carbonate (material samples demonstrate logarithmic scale rather than linear). The scattering increase can be attributed to photons bouncing of one another rather than transmitting directly through the material. Therefore, the material will appear more visibly

Image compares two membrane thicknesses of the same value.

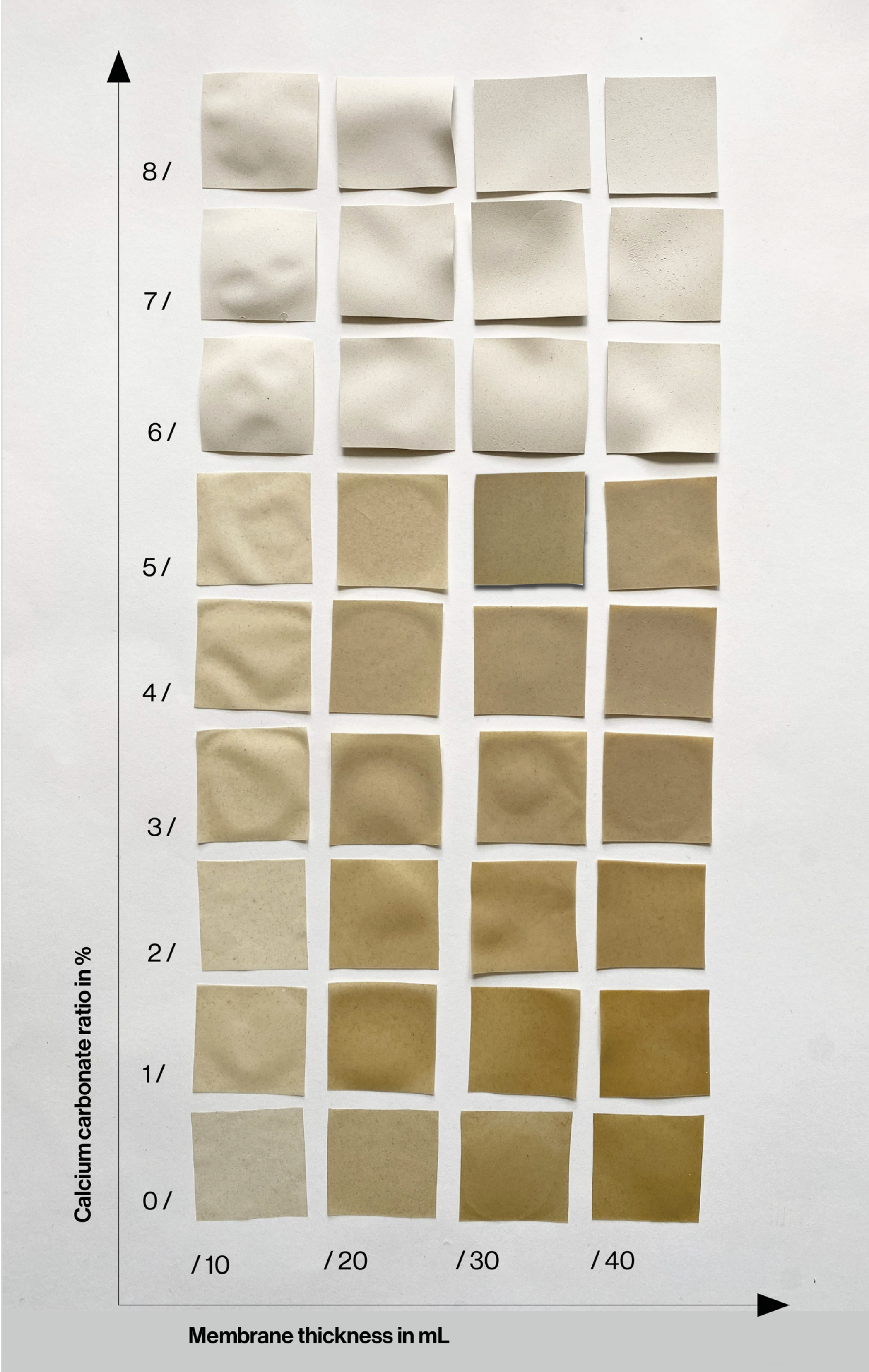
opaque to the human eye as the ratio of calcium carbonate increases.

The thickness of the carrageenan iota membrane was an additional variable explored to alter the optical density / light transmission of the material which follows Lambert-Beer Law for attenuation.

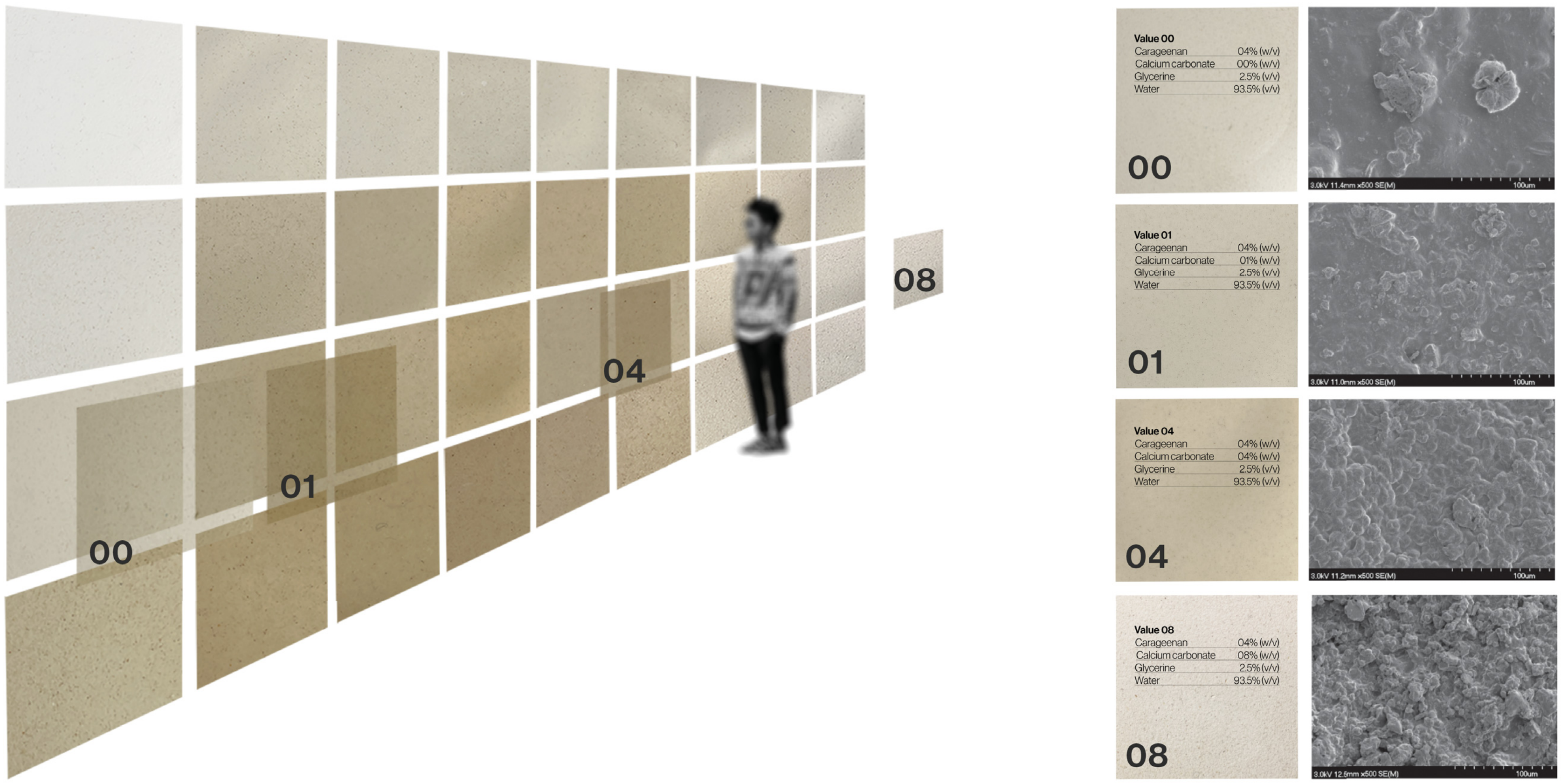
For the study these two variables (variable 1: calcium carbonate content, variable 2: membrane thickness) were organized in an adapted Munsell colour chart to comparatively assess the change in optical properties. On the chart, the x-axis represents membrane thickness and y represents weight for volume percentage of calcium carbonate additive. For the calcium carbonate values, each gradation from 0%-8% of w/v calcium carbonate additive were poured in 3” diameter circular bamboo formwork. Within this spectrum four values of membrane thickness were poured, 10mL, 20mL, 30mL and 40mL. 36 samples were organized in the adapted Munsell chart.

Analysis 2. Warping Study

Carrageenan as a membrane has a tendency to warp as it dries. The following analyses seek to identify the variables of warping to determine how much control the designer has over this process. Variables that were found to affect warping are membrane thickness, calcium carbonate addition, glycerine addition, and formwork. The Warping 01 study



Adaptation of Munsell colour chart showing membrane thickness on the x axis and calcium carbonate ratio on the y axis.



Value 00

Carageenan	04% (w/v)
Calcium carbonate	00% (w/v)
Glycerine	2.5% (v/v)
Water	93.5% (v/v)

Value 01

Carageenan	04% (w/v)
Calcium carbonate	01% (w/v)
Glycerine	2.5% (v/v)
Water	93.5% (v/v)

Value 04

Carageenan	04% (w/v)
Calcium carbonate	04% (w/v)
Glycerine	2.5% (v/v)
Water	93.5% (v/v)

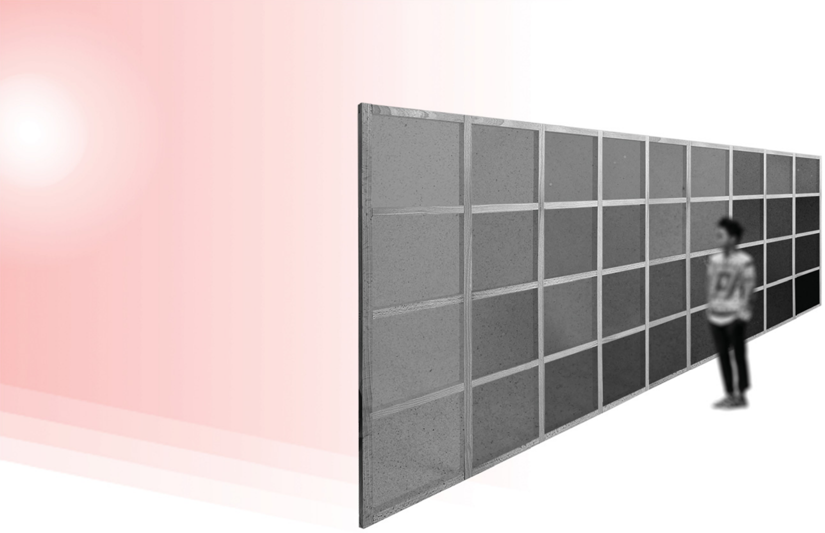
Value 08

Carageenan	04% (w/v)
Calcium carbonate	08% (w/v)
Glycerine	2.5% (v/v)
Water	93.5% (v/v)

Samples for adaptation of Munsell colour chart, from left to right: 00, 01, 04 and 08 shown with corresponding SEM courtesy of Patricia Scallion.

Adaptation of Munsell chart shown inhabited. This image demonstrates how translucency will vary as a function of membrane thickness and calcium carbonate ratio.

Adaptation of Munsell shown with incident light demonstrating reflectance.



Adaptation of Munsell shown with back lighting demonstrating optical density.

looks at the relationship between membrane thickness, calcium carbonate addition and warping. The Warping 02 study looks specifically at calcium carbonate addition.

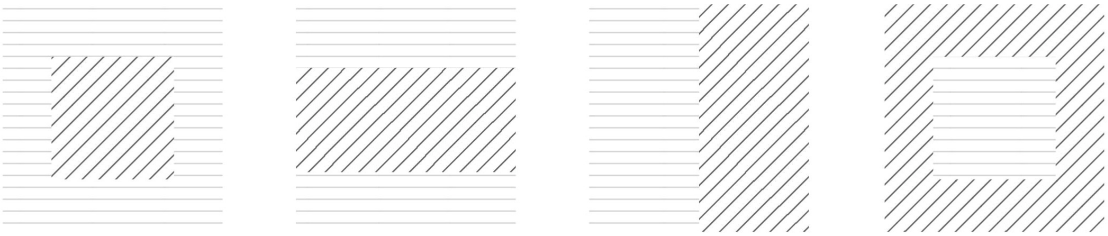
Warping Study 01

The membranes compared in this study were two 2% w/v calcium carbonate values and one 3% w/v calcium carbonate value. There was a difference in thickness between the 2% w/v calcium carbonate membranes with one being <1mm and the other being 1mm. The shrink/warp ratio of all three membranes was calculated based on the surface area of the original pour. The membrane with the highest shrink/warp rate was the thicker 2% membrane. A takeaway from this was understanding the thinner the pour, the greater the dimensional stability of the material.

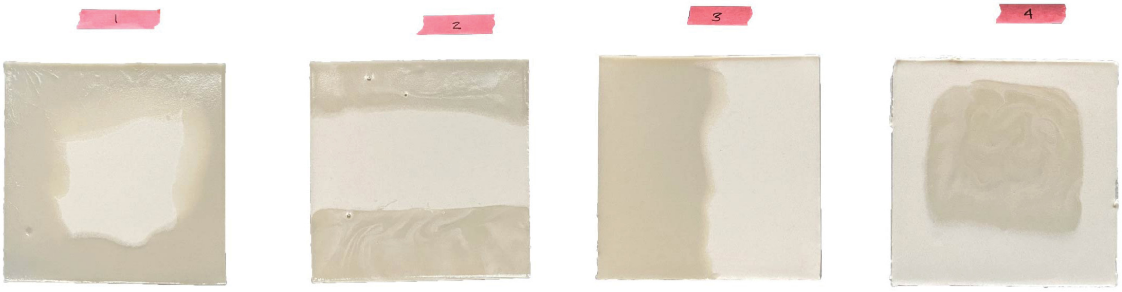
Opacity was presumed to be determined by calcium carbonate addition, but this study also reveals that opacity is related to membrane thickness (as per Lambert-Beer Law). All the membranes have variable surface areas that are thinner in some areas and thicker in others. When observed on the light table these thin areas appear more translucent than thicker areas. Unlike glass, which can come in multiple thicknesses and remain relatively transparent (although optical properties will be altered), the carrageenan membrane shifts its optical density as a function of membrane thickness.

Warping Study 02

Warping study 02 was carried out to determine how multi-material carrageenan pours affected the warping of the material. The purpose of this study is to see if a multi-material approach could be used as a tool for additive manufacturing

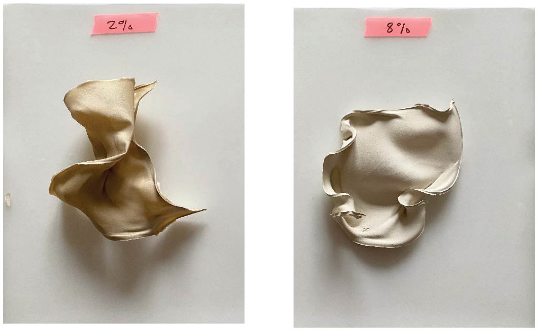


2% **8%** Multi material pattern



Day 01, T= 1 hour

Day 05, multi-material pattern



Day 05, control samples

Value 02

Carageenan	04% (w/v)
Calcium carbonate	02% (w/v)
Glycerine	2.5% (v/v)
Water	93.5% (v/v)

Value 08

Carageenan	04% (w/v)
Calcium carbonate	08% (w/v)
Glycerine	2.5% (v/v)
Water	93.5% (v/v)

Warping study 02: Multi-material warping study with two values of calcium carbonate addition in four patterned pours.

Composition

Warping pattern

Shrink / warp percentage

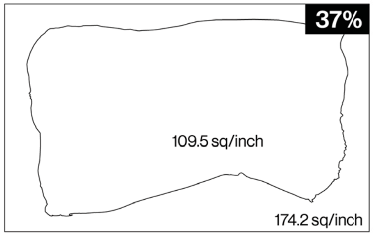
Translucency

Value 02

Carageenan	04% (w/v)
Calcium carbonate	02% (w/v)
Glycerine	2.5% (v/v)
Water	93.5% (v/v)

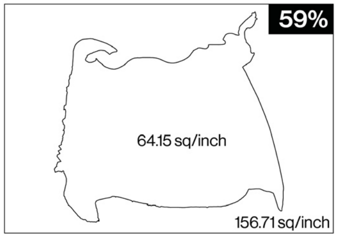
Value 03

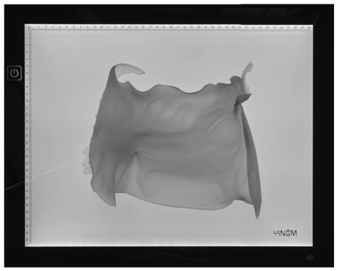
Carageenan	04% (w/v)
Calcium carbonate	04% (w/v)
Glycerine	2.5% (v/v)
Water	93.5% (v/v)



Value 02

Carageenan	04% (w/v)
Calcium carbonate	02% (w/v)
Glycerine	2.5% (v/v)
Water	93.5% (v/v)





Warping study 01: Analysis comparing warping pattern, shrink / warp percentage and translucency of carrageenan calcium carbonate composite.

where rather than relying on formwork to hold material onto substrate, a different gradation of material could be printed as a skirt that would function to control warping. In this study 2% and an 8% calcium carbonate solution were poured in different patterns in identical formwork to see if warping could be controlled through material layout.

01 Poured with 2% exterior band and 8% interior. This sample was expected to warp the least but ended up warping the most.

02 A band of 8% is framed on two sides by 2% value. This sample warped the least of the four.

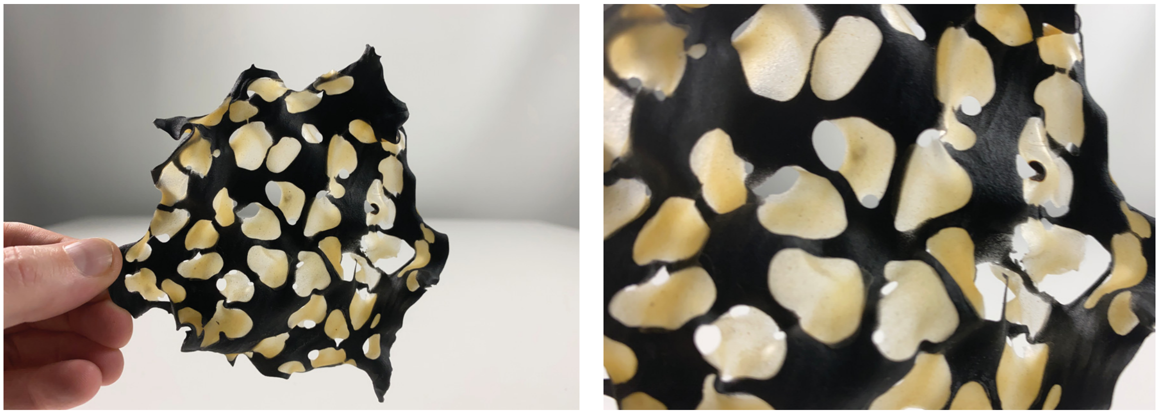
03 Sample three was poured in two halves, with 2% on the left and 8% on the right. The 2% side warped much less than the 8%.

04 The last sample is an inverse of the first, with an 8% exterior band framing a 2% interior square. This material sample warped almost as much as sample 01.

The formwork and the material volume were kept as controls so that the membranes all had identical surface areas and thickness. As well, glycerine was not added to this study. Two controls were also poured to compare their warp as well. The results from Warp 02 are relatively inconclusive. This multi-material approach requires further experimentation to hone this variable into a design parameter.

Analysis 3. Cohesion

Carrageenan iota is a self healing material. When it tears, it can be hydrated and it will re-crosslink to form a continuous bond. This particular material behavior results in cohesion between membranes, meaning pours done in the same

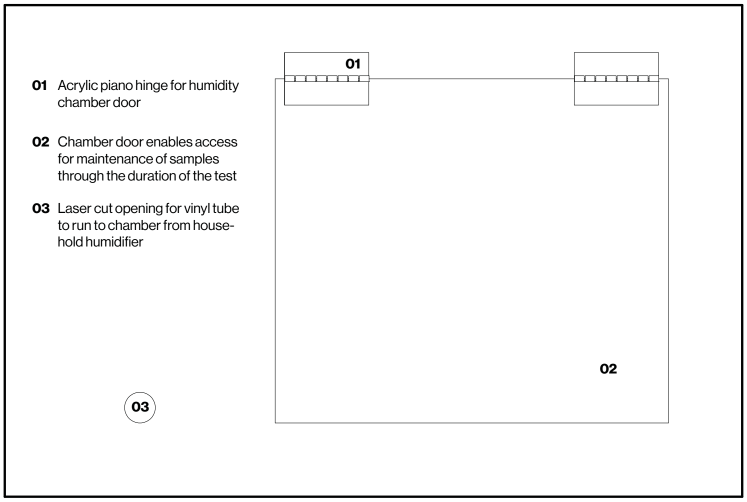


Material samples of carrageenan iota and biochar composite demonstrating cohesive properties

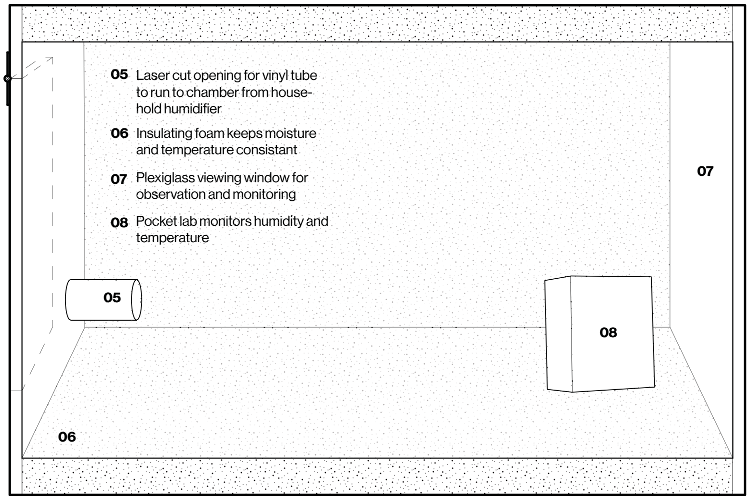
place with adjacent sides will co-hese into a relatively seamless membrane. Although not included in the scope of this report, in additive manufacturing applications, the property of cohesion could also enable a skin or base layer of carrageenan to be printed with multiple layers of the same or varied composition printed on top. The toolpaths used to deposit the material, the thickness of the membrane layers and the composition of the additive could be potentially programmed to vary the material properties of the membrane. Once this layered system of carrageenan dried it could perform as a single membrane with heterogenous properties.

Analysis 4. Decomposition

The constituent macromolecules extracted from seaweed, mollusc shells and plant matter - carrageenan, calcium carbonate and cellulose - all have different levels of responsiveness to environmental factors such as heat, humidity, and light. To test responses to humidity, a humidity chamber was built to observe decomposition responses. The chamber was comprised of four walls of insulating foam and two plexiglass sheets which enabled the samples to be monitored without altering the interior conditions. A poly tube was run from a household humidifier into an opening in the back of the chamber. The system was monitored using a Pocket-lab Weather device measuring humidity, temperature, and light exposure. Over the course of two weeks the materials were held between 90-100% RH and 21 degrees Celsius. Identical models to the ones that were placed in the humidity chamber were kept as controls to compare degradation. The variable for comparison was that they were held in an environment that maintained a relative humidity of less than 50%. The controls maintained were



Humidity Chamber Back Elevation



Humidity Chamber Side Section

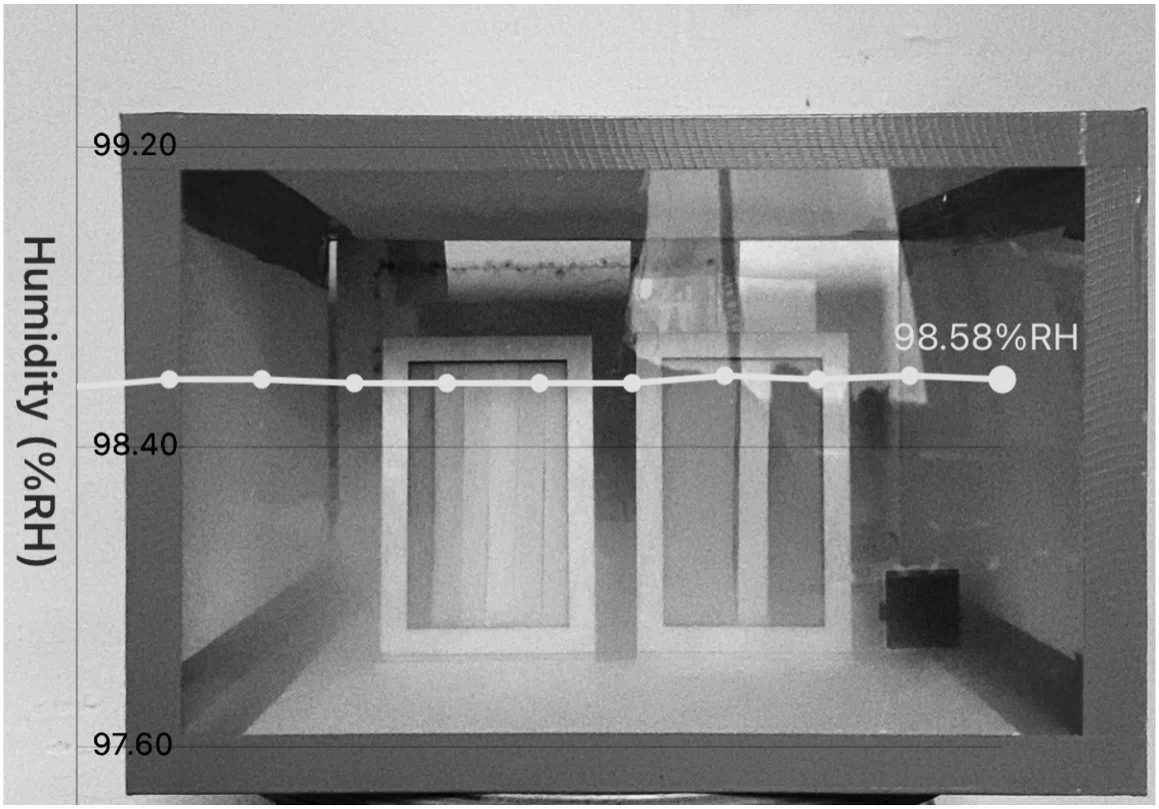
Diagrams of humidity chamber design and set up.

Photograph of humidity chamber set up.

that they were held at the same temperature as the models in the humidity chamber and were exposed to the same amount of light.

The photo analysis shows the degradation of the materials in relationship to time. The humidity chamber analysis showed that membranes with a lower w/v of calcium carbonate to carrageenan tended to degrade faster. The materials that were held at less than 50% RH maintained their form over the course of the month. These studies suggest that by combining input ingredients for the bio composites in different ratios, the level of environmental responsiveness can be programmed or adjusted within the material. External environmental forces like temperature, irradiance and humidity contribute to the degradation of biomaterials whether slowly, or quickly. Data from both the macroscale environmental conditions and chemical compositions at the molecular scale can be optimally tuned for a desired outcome.

Decomposition analysis comparing biomaterial membrane models held at 50% RH and 100% RH over the course of several weeks.



Photograph of models in the humidity chamber at 98.6% RH from Pocket Lab Weather app.

These outcome from these analyses point to the potentiality to work precisely with materials in design. A larger ambition of the work is towards a design methodology where material properties are harnessed to generate form. Specific explorations presented in following section primarily work from the data collected in Analysis 1. This is to produce a focused working method for biomaterial design which can be expanded to include the other material properties analyzed. Given the trans-scalar engagements of the biomaterials and organisms they are derived from, material behavior can also be considered and programmed at multiple scales. The next section will demonstrate studies that engage biomaterials across scales by blending macromolecule components at the microscale to create gradations of material, controlling

Image demonstrating the idea of an experimental garden, a field testing site where designers can monitor and analyse material behavior in response to environmental forces.

the distribution of material at the meso scale through fabrication, and through a relationship between material and optical properties, or material and perception at the human scale. These low-tech studies are just beginning to touch on what is possible when material and microstructures are engaged within the domain of design.

Chapter 5: Material-Based Design Experiments: Gradient Scales and Multi-Value Membrane

From the astronomical to the nanoscale this research presumes that perception beyond human scale is vital to a creative participation with nature (Cajete 2000, 21). Through the process of working with these materials the author experienced that novel trajectories are revealed when both designer and materials are attuned with one another and the surrounding environment. The following investigations, gradient scales and multi-value membrane extend the typical domain of architecture: floor, wall and roof to material, body and environment. These design experiments disrupt a conventional design process by putting material at the forefront of the exploration. This disruption foregrounds a pressing question about the ways in which design methodologies can either limit or expand material agency. Therefore, these inquiries begin with an ambition to be driven primarily by material behavior rather than formal conventions.

The experiments encompassed in gradient scales and multi-value membrane show a range of material focused design explorations that were carried out over Thesis I and II. The purpose of these studies was to develop tacit material knowledge, as a material inquiry into the relationships that exist between scales and for opportunities to put practice before theory as demonstrated by Albers.

Gradient Scales

As demonstrated in Chapter 4, through combining inputs in different ratios, a composite can be generated that displays

Detail of gradient scales model showing variable translucency as a function of calcium carbonate.

a variation in material properties. A brittle membrane can be made flexible through the addition of a small amount of glycerine, while increasing the proportion of calcium carbonate adds a structural rigidity. A vast diversity of combinations is possible from a limited palette of constituents. Made from primarily the same few constituent elements, properties of many natural composites vary as a function of material gradation and microarchitectures (Benyus 1997). Drawing from nature's wisdom, gradient scales demonstrates composite material membranes that exhibit variations in optical density, flexibility, and tensile strength. The composites have been developed from four inputs: water, carrageenan iota, calcium carbonate and vegetable glycerine.

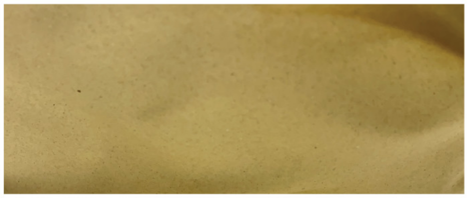
Gradient Scales programs material components with a gradation of opacity. Increasing ratios of calcium carbonate are suspended in a matrix of carrageenan, resulting in a spectrum of translucency described by five determined values. I chose a material gradation of 0%, 2%, 4%, 6% and 8% for gradient scales for their clear visual gradation. The quantified material values become a design parameter

Value 01

Carageenan	04% (w/v)
Calcium carbonate	00% (w/v)
Glycerine	2.5% (v/v)
Water	93.5% (v/v)

Value 02

Carageenan	04% (w/v)
Calcium carbonate	02% (w/v)
Glycerine	2.5% (v/v)
Water	93.5% (v/v)

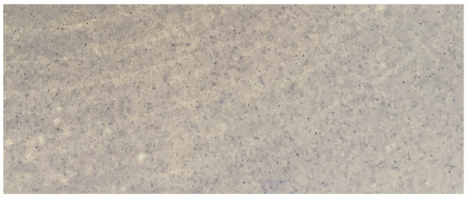


Value 03

Carageenan	04% (w/v)
Calcium carbonate	04% (w/v)
Glycerine	2.5% (v/v)
Water	93.5% (v/v)

Value 04

Carageenan	04% (w/v)
Calcium carbonate	06% (w/v)
Glycerine	2.5% (v/v)
Water	93.5% (v/v)



Value 05

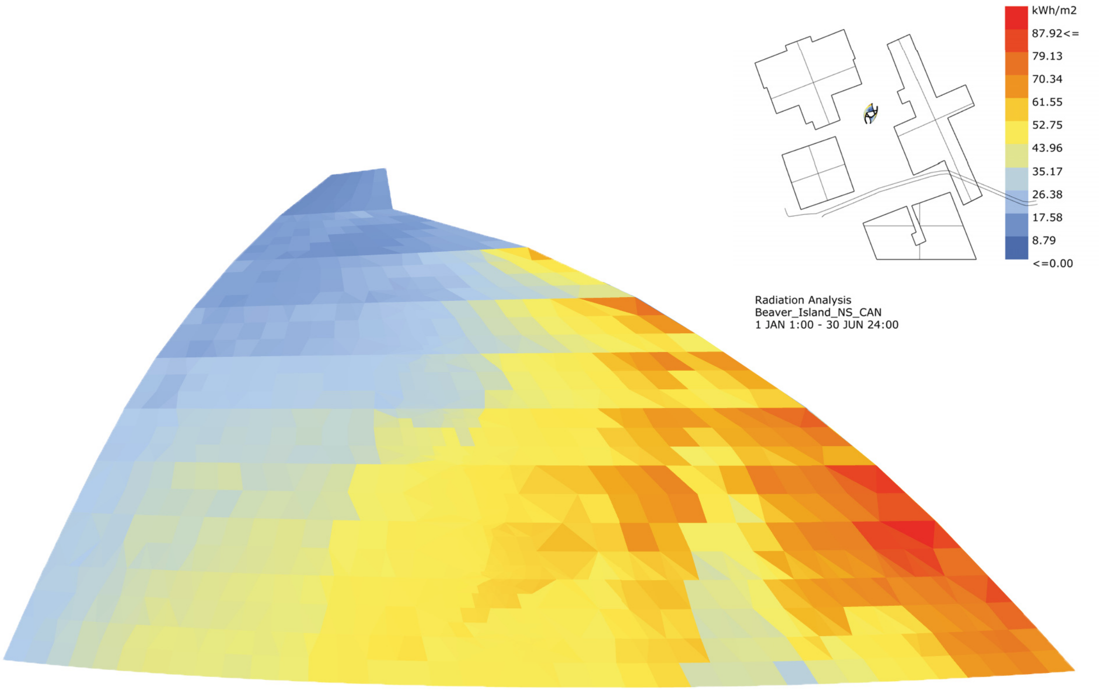
Carageenan	04% (w/v)
Calcium carbonate	08% (w/v)
Glycerine	2.5% (v/v)
Water	93.5% (v/v)

Compositions generated for gradient scales by mixing concentrations of calcium carbonate into a carrageenan iota biopolymer matrix which generated five values. 2021.

The structure of gradient scales pavilion is comprised of steam-bent beech.

whereby light can be modulated at the architectural scale through changes in the material at the molecular scale. This enables gradient scales to move beyond a binary code of window or wall, transparent or opaque, and into a complex system of varied light attenuation that can be tuned for variable functions and environments.

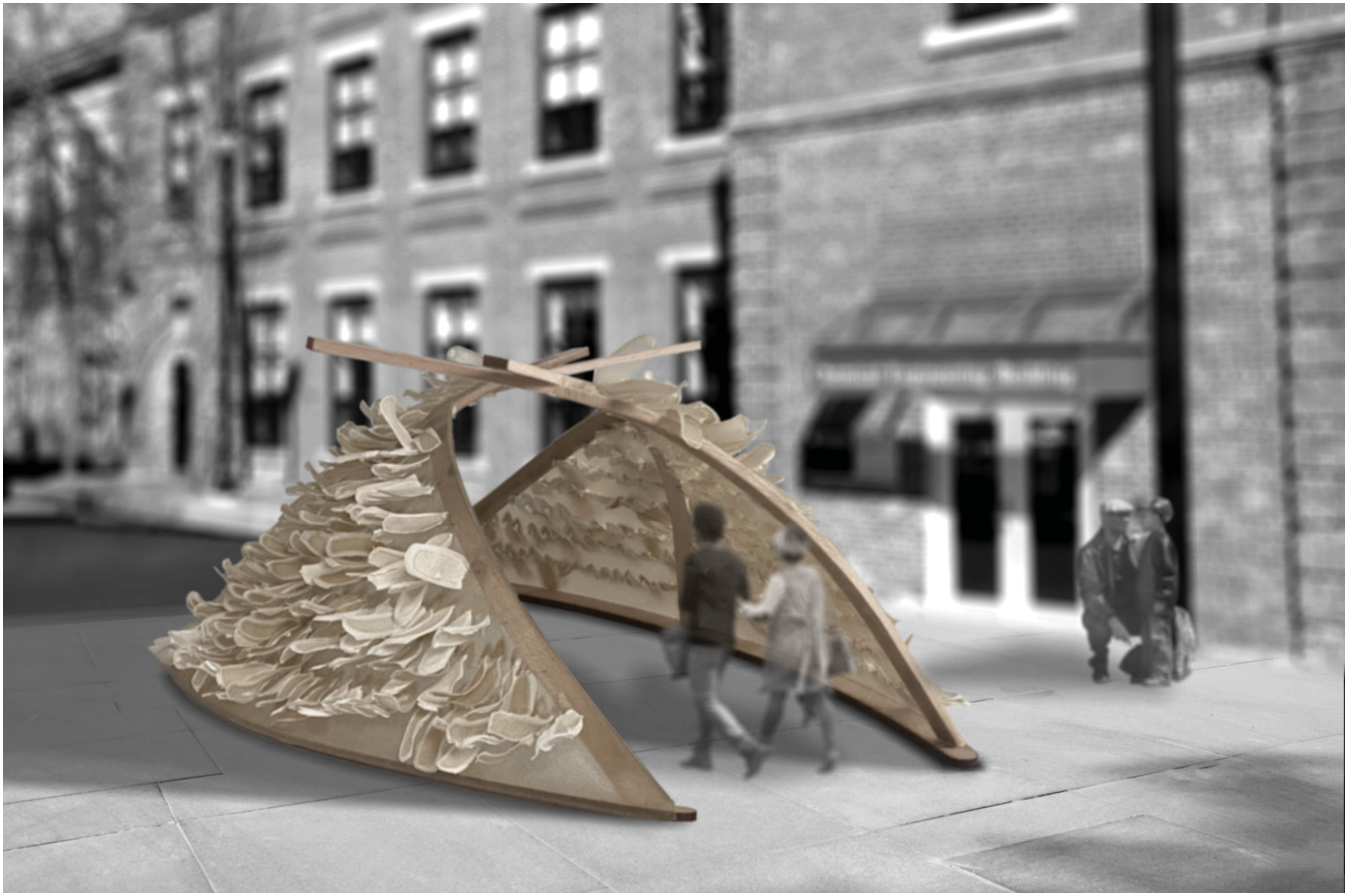
Building on the material gradation, gradient scales tests the ability to translate these variable optical values to geometry in relationship to environmental forces. The gradient scales pavilion is comprised of two curved structures wrapped in a carrageenan iota membrane and patterned with hundreds of tiny scales that mimic the scales on a butterfly wing. In Rhinospace, a 3D model of wing pavilion was located within the building context of Dalhousie School of Architecture and



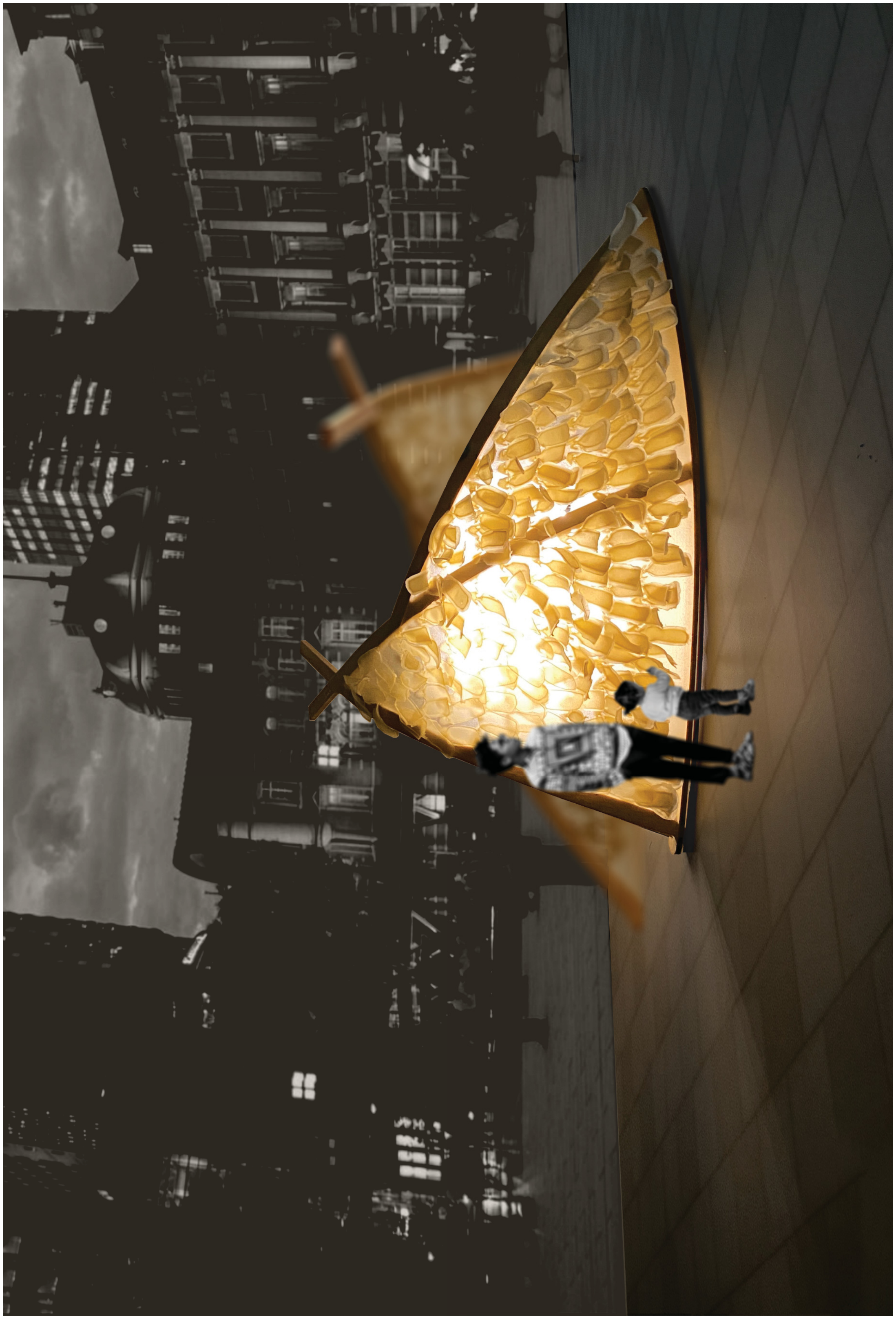
Gradient scales solar radiation map values projected on pavilion surface.

a radiation map was generated that determined the amount of solar radiation to which the gradient scales would be exposed over the course of one year. The radiation map was meshed into a grid of similar scale to the physical components, with a value of translucency assigned to each scale.

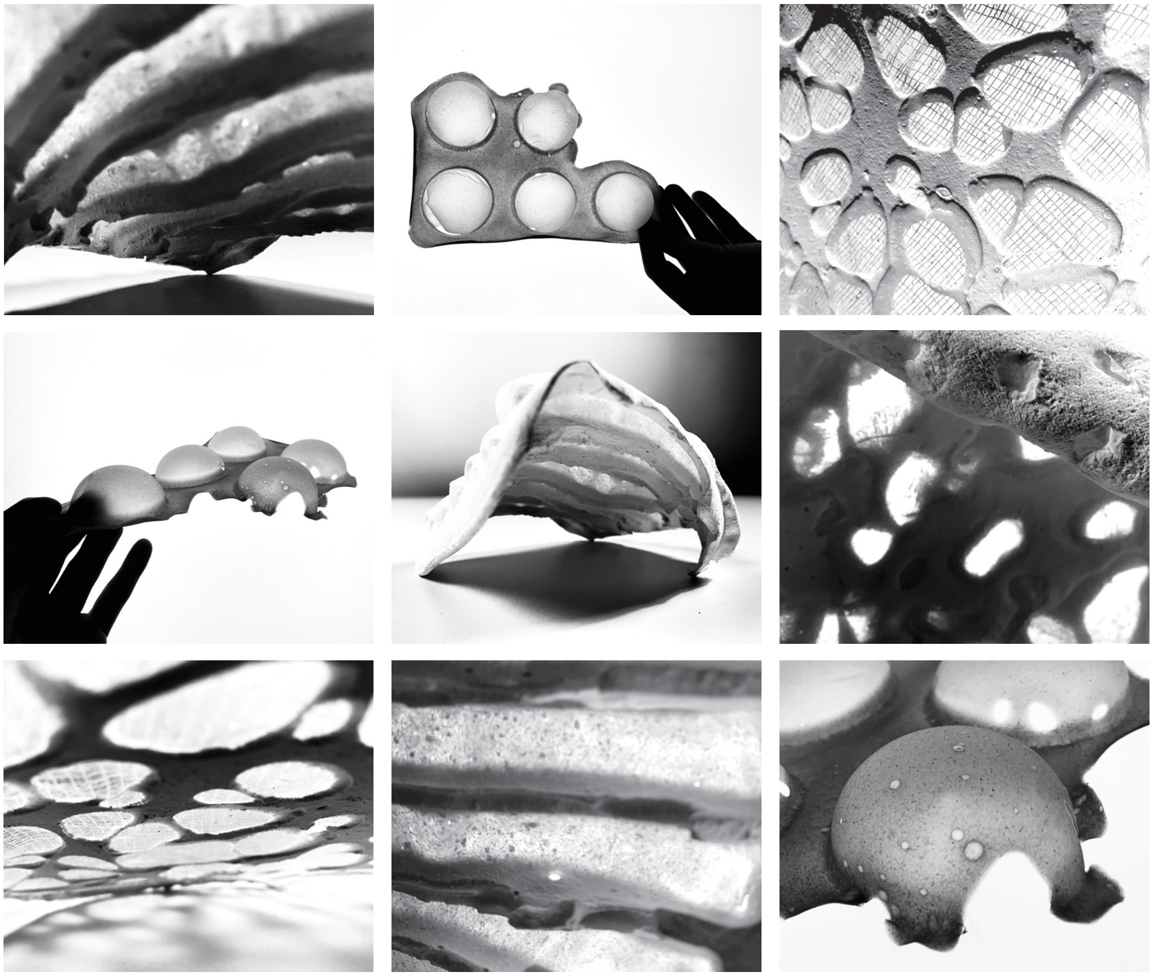
The areas with less solar radiation (rendered in blue) were assigned the most translucent value, and the areas with higher levels of solar radiation (rendered in red) were assigned more opaque components. Therefore, the amount of light transmitted through the pavilion wall is modulated by the patterned attenuation of the scales. This logic can be applied to different sites to generate different patterns of scales, or for different experiences of light. During the day, the gradient scale transmits light from the sun to



Gradient scales pavilion inhabited during the day.



Gradient scales pavilion inhabited at night.

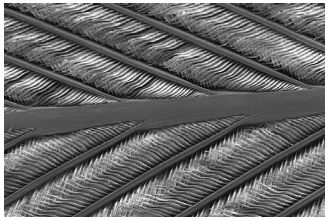
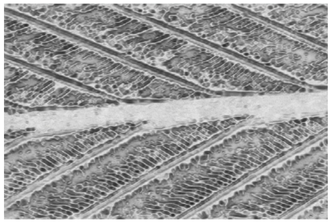
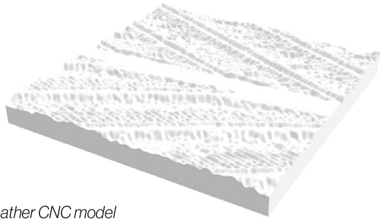
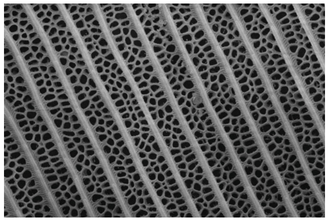
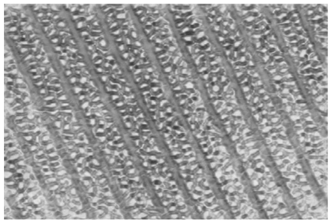
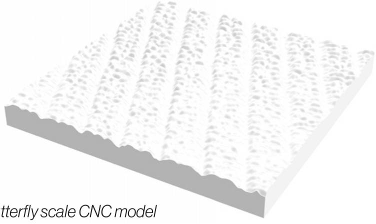
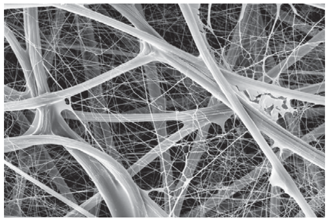
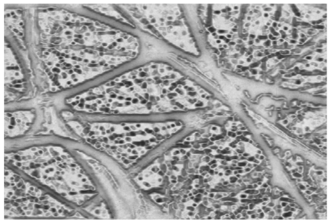
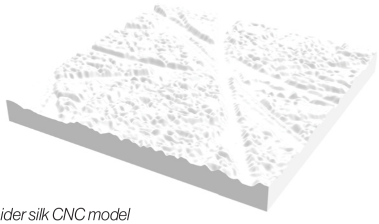


Initial material explorations by author in programming a single membrane with multiple values of translucency. Base compositions are sodium alginate and carrageenan iota with calcium carbonate additives.

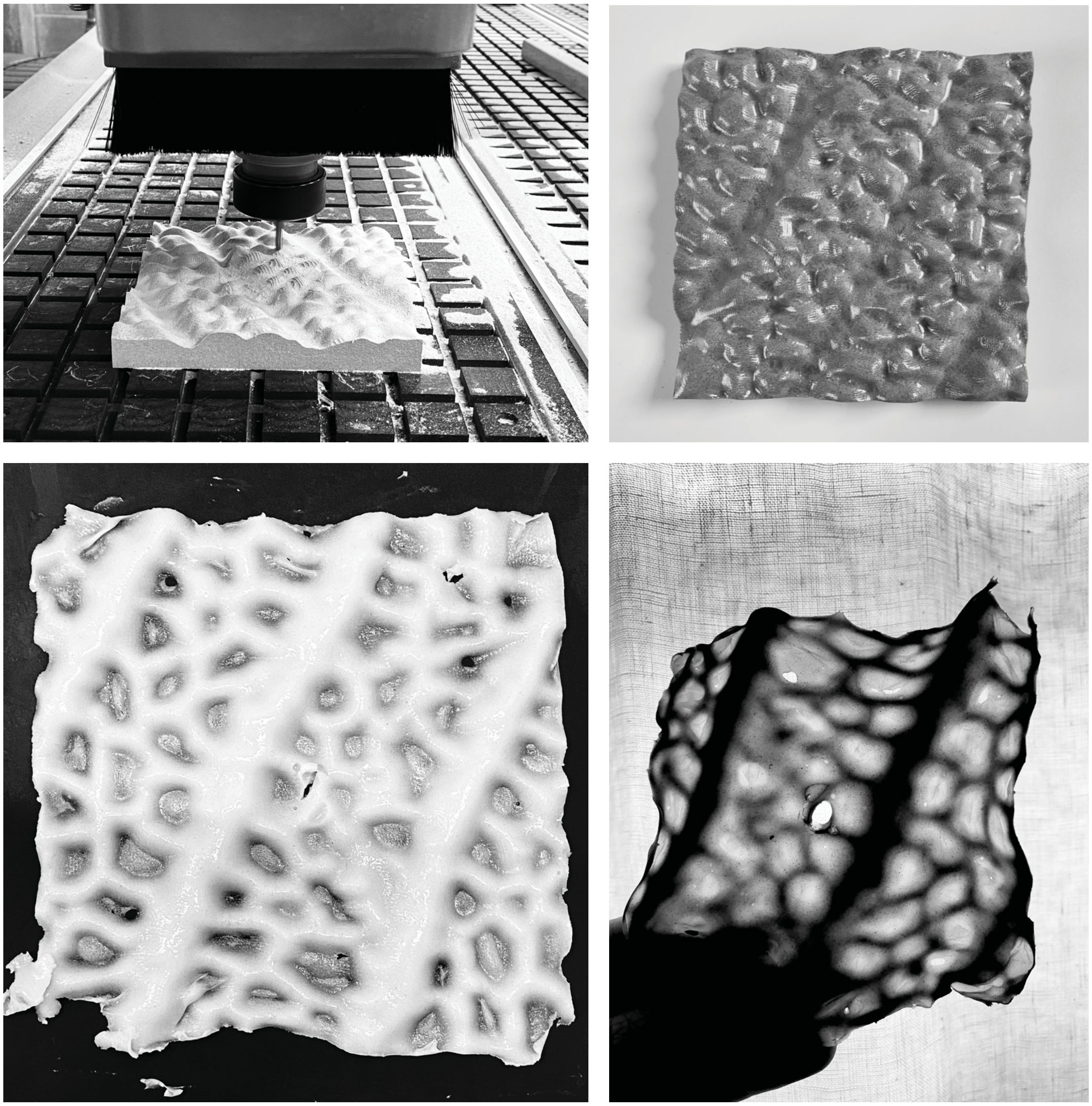
interior spaces, and at night it works in reverse, becoming a patterned lantern that illuminates from the inside out.

Multi-Value Membrane

This design experiment is multifaceted: but at its core it is an extension of Gradient Scales. Multi-value membrane takes the notion of a variable material composition and applies this concept to a single membrane. Running parallel to this inquiry is a biomimetic study into microstructures found in nature. The underlying question of multi-value membrane is how to evaluate variable translucency within a single

	Scanning Electron Micrograph	**complex surface geometry**	**CNC model of surface**
feather example of structural colour: hummingbird feathers have optically complex stacks of hollow, platelet shaped organelles called melanosomes optical properties: iridescence	 *feather SEM* *350x scale* *image credit: Steve Gschemeissner*	 *feather inverted* *resolution 150 x 150* *heightfield 10mm, interpolate surface*	 *feather CNC model* *dimensions 38.1 x 38.1 x 3.81 cm* *surface area 1812 cm2*
butterfly scale optical properties: capable of absorbing 99.95% of photons cellular material	 *butterfly scale SEM* *10 000x scale* *image credit: Amanda Amori*	 *butterfly scale inverted* *resolution 150 x 150* *heightfield 10mm, interpolate surface*	 *butterfly scale CNC model* *dimensions 38.1 x 38.1 x 3.81 cm* *surface area 1782 cm2*
spider silk mechanical properties: -tensile strength is similar to that of alloyed steel -high elasticity -ductility: can stretch five times its relaxed length without breaking	 *spider silk SEM* *unknown scale* *image credit: Thierry Berrod*	 *spider silk inverted* *resolution 150 x 150* *heightfield 10mm, interpolate surface*	 *spider silk CNC model* *dimensions 38.1 x 38.1 x 3.81 cm* *surface area 1766 cm2*

A series of scanning electron micrographs of natural structures that have been put through a heightfield algorithm and meshed for CNC milling, from top, a feather, butterfly scale and spider silk. (Amori 2019; Berrod 2017; Gschemeissner n.d.)



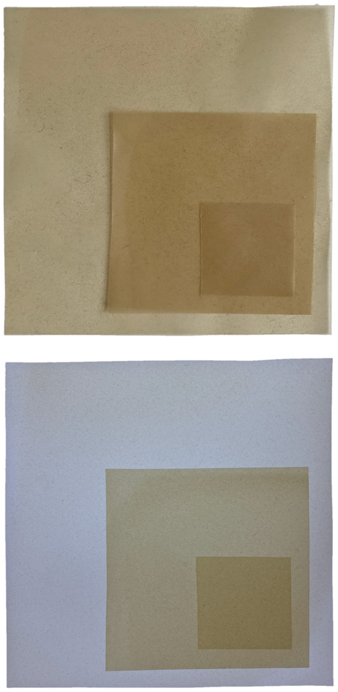
Scale magnified 10,000 times. From top left: CNC into melamine surface that was used as formwork for membrane casting, carrageenan membrane showing heterogeneous translucency.

membrane as a function of material composition, material deposition and surface area.

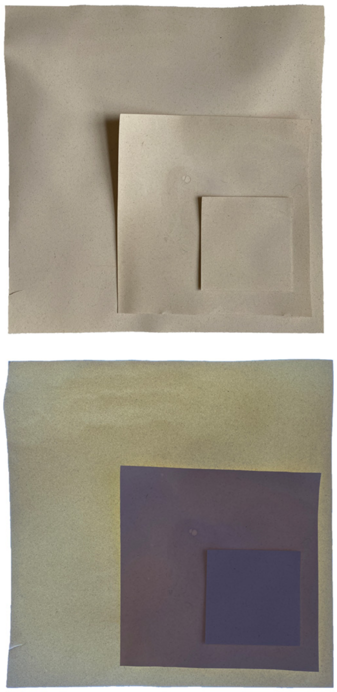
From a study of scanning electron micrographs (SEMs), microstructures found in nature - a butterfly scale, spider silk and a pigeon feather - were analyzed and fabricated. The author chose to analyze these specific natural microstructures because of their interesting optical properties at the human scale. Like Gradient Scales, Multi-value Membrane explores a material composition of carrageenan and calcium carbonate, but with heterogenous optical and mechanical properties that are a function of material thickness and surface area.

The author inverted SEM images and meshed them in 3D modelling software in preparation for CNC milling. These images were projected from two dimensions into three dimensions using a heightfield algorithm. Using a CNC router, the complex surfaces of microstructures were then milled into stock, which was used as formwork for the biopolymer. The biopolymer composites were mixed with a 4% w/v ratio of calcium carbonate to carrageenan. Two studies were carried out – one with a thinner membrane pour and one with a thicker pour. The thinner membrane dried with less surface warping than the thicker membrane, which deformed quite drastically.

Compared to a single component from Gradient Scales that demonstrates a homogenous value, the results of this study suggest that both optical properties and mechanical of the test membranes have been augmented as a function of the varying thickness of membrane determined by surface area geometry. The possibilities for fabricating a heterogenous carrageenan iota membrane are amplified with Additive Manufacturing platforms, therefore future iterations of Multi-value Membrane could be explored through 3D printing.



Layering of value 00 carrageenan membrane showing reflectance (top image) and optical density (bottom image)



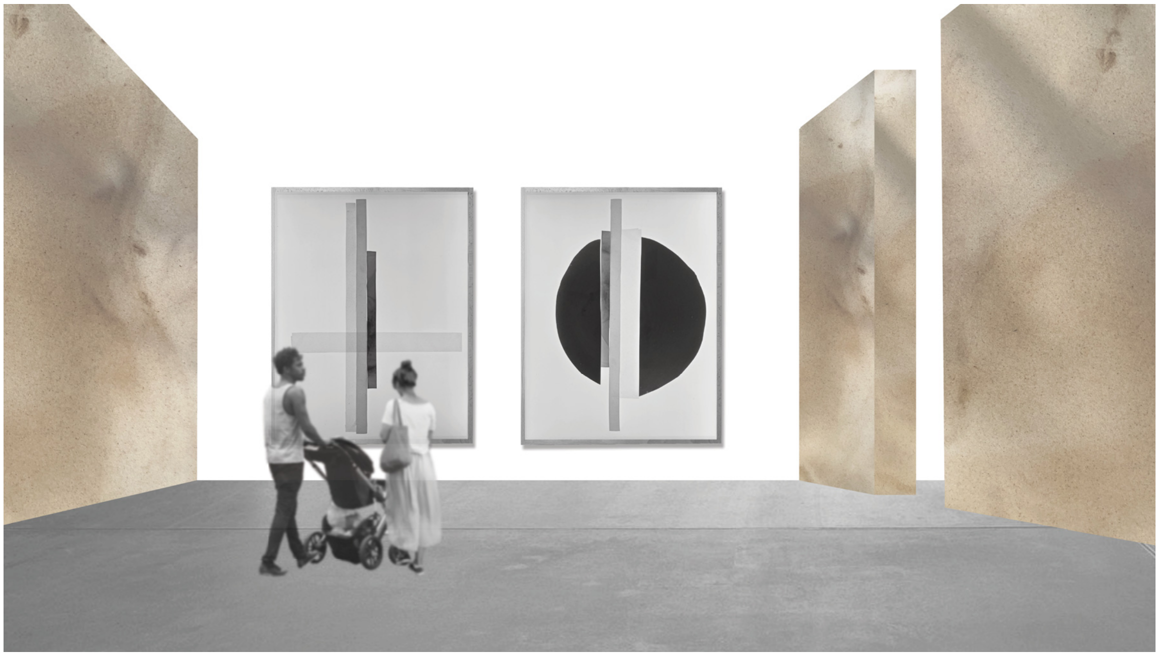
Layering of value 08 carrageenan membrane showing reflectance (top image) and optical density (bottom image)

Chapter 6: Structural Optics: A Case Study in Facades

Biomaterial membranes made from carrageenan and calcium carbonate have an impressive array of material behaviors but have rarely been explored as building materials. The previous studies offer a glimpse into the many possible directions this thesis could explore. However, it was through paring down the membranes into linear planes and comparing values from the Munsell adaptation that the author began to hone a subjective ‘material sight’. As Josef Albers demonstrates in his colour exercises, “a thing is never seen as it really is” (Albers 1963, 1). Colour is relative. It is experienced almost always in relation to another colour. Translucency is like colour in that regard; a material is almost always experienced in relation to another material that has a greater or lesser optical density. Drawing from tacit knowledge developed in the material-based design experiments, the following studies presented as an exhibition installation explore visual perception of the carrageenan calcium carbonate membranes at the human scale through a case study in two dimensional planes and facades.

Translucency Study

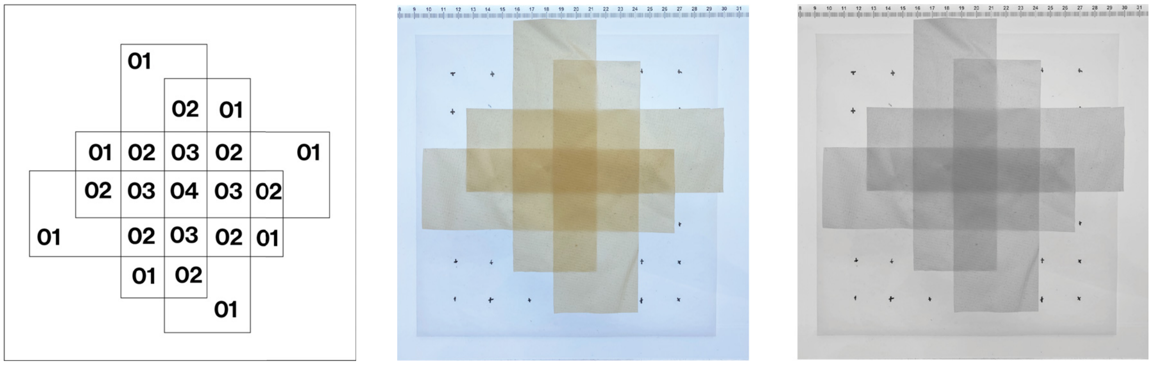
The layering of translucent materials produces emergent colours and optical phenomena. Changing solar conditions will alter perception of membranes as each gradation of membrane has a unique optical density and reflectance value. The higher the ratio of calcium carbonate in the membrane, the higher the optical density will be. When lit from behind, the membranes will appear the darkest. When



Exhibition view of two dimensional transparency studies following Albers.

incidence light is directed towards the surface, membranes with the highest optical density value will also appear the brightest. Further, the optical phenomenon of translucency augments spatial boundaries as the material becomes a filter through which qualities derived from the material are imbued on the experience of space. This material-filter phenomenon is demonstrated in The Beinecke Rare Book & Manuscript Library at Yale, where thin sheets of marble enclose the building. As these translucent panels are lit from exterior solar radiation, they appear to glow, highlighting variations in the veined material, while direct visual reference to the outside is filtered out.

The layering of translucent material produces optical phenomenon. One of these effects is described by the Weber Fechner Law, which explores the relationship between perceived change and actual change. Experimenting with layering the biomaterial membranes in a demonstration from

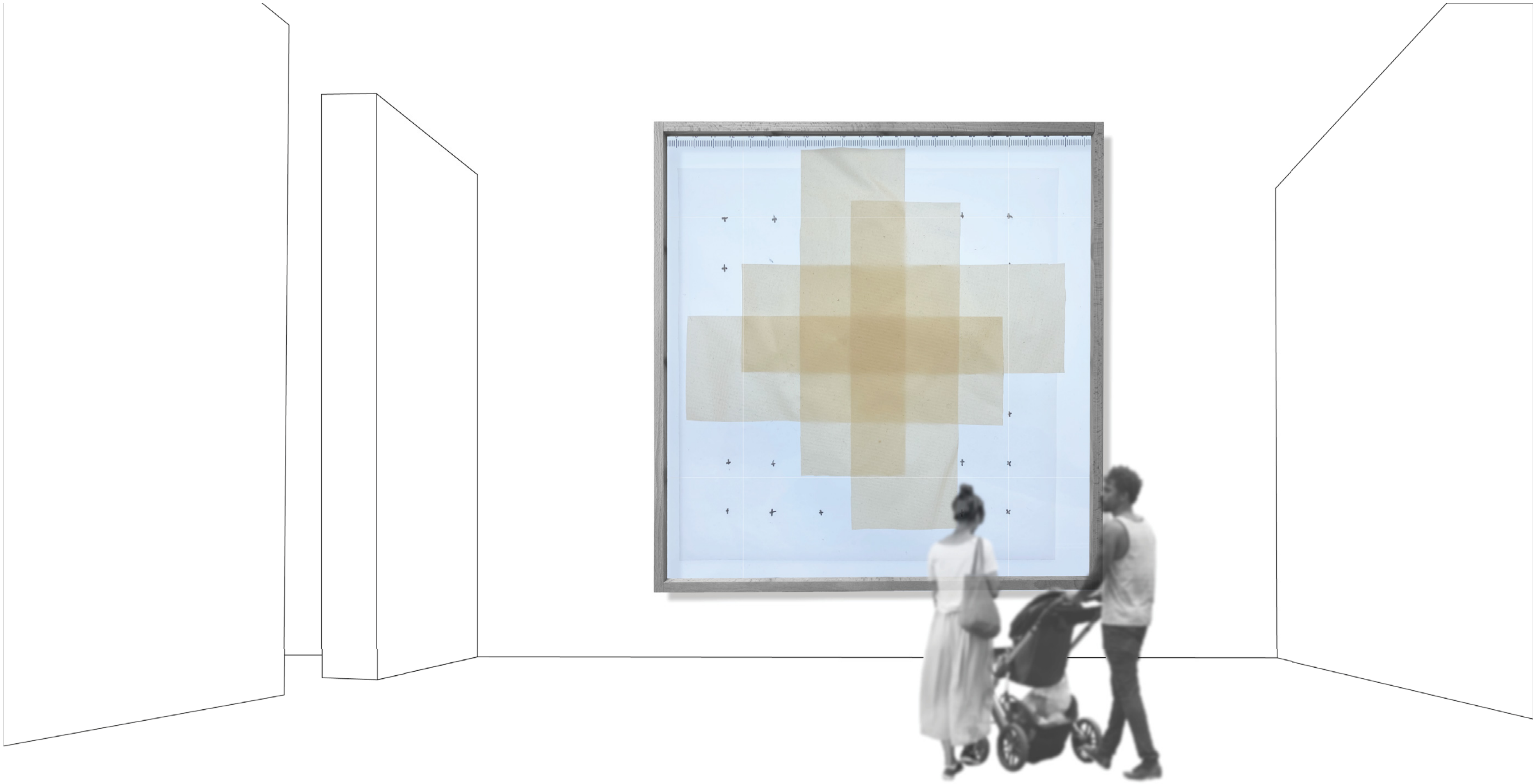


Biomaterial demonstration and analysis of the Weber Fechner law of perceived change vs actual change.

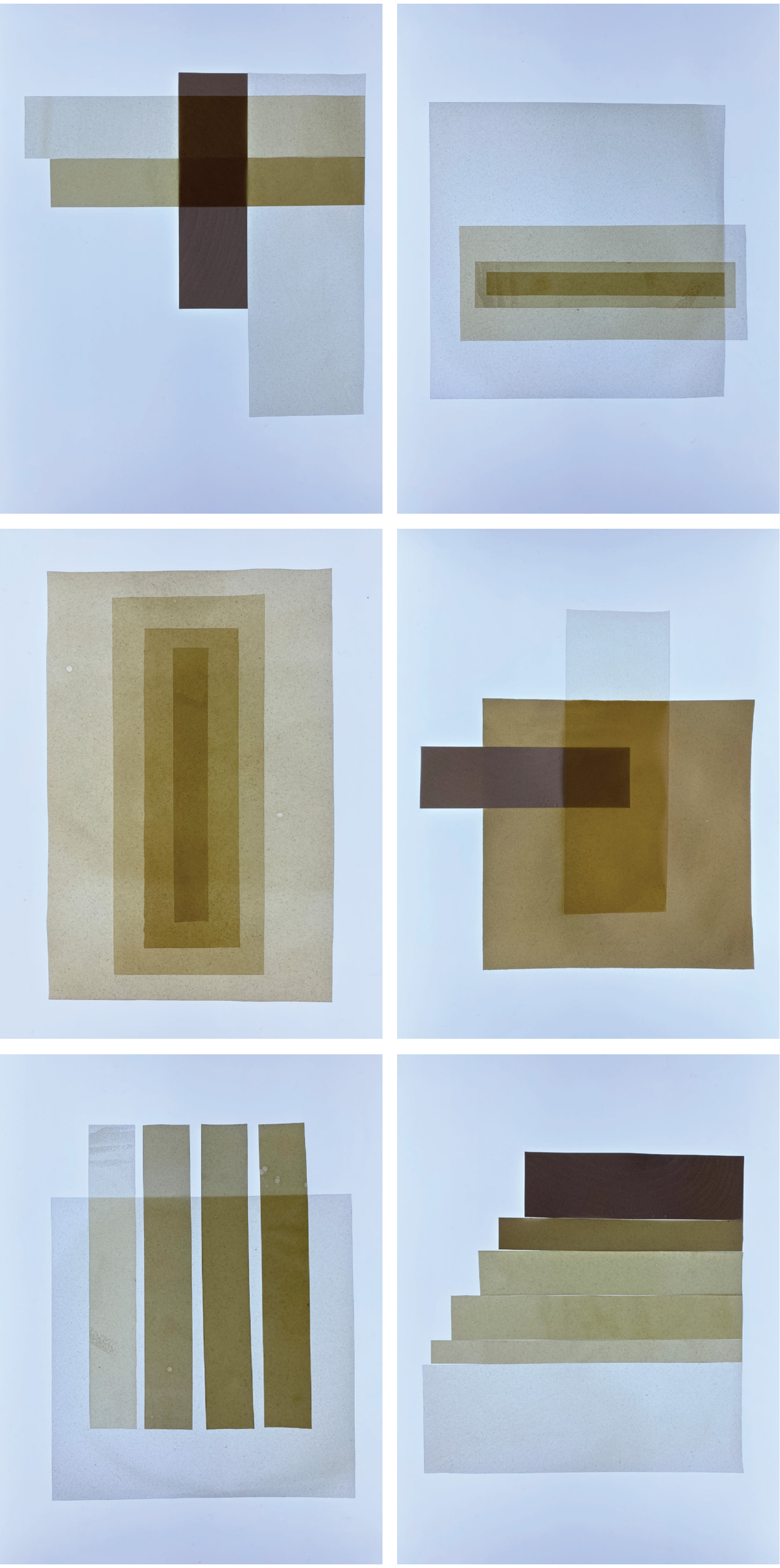
Albers Interactions with Colour, four equal rectangles of the same translucency overlap each other creating four distinct values from a single value. The boundaries between layers become less defined as the number of layers increase. Extending the Weber Fechner Law, the author experimented with layering multiple values of translucent membranes on a flat plane.

This resulted in creating the effect of spatial dimensions where there is none. As this study progressed more questions arose: could three dimensions appear as two, and if so, how might reflectance vs optical density offer contrasting material readings depending on the direction of incidence light. What is the threshold angle of incidence between optical density and reflectance? Can it be quantified? To explore these questions, further layering studies were carried out in three dimensional models.

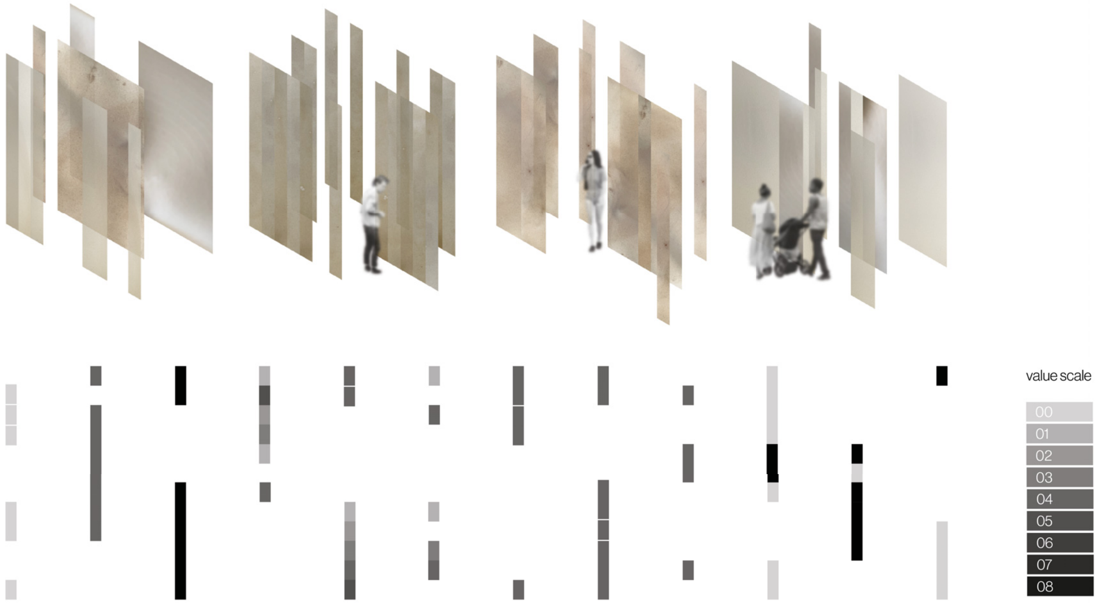
Projecting from two dimensions into three, a procession through different experiences of light have been sequenced through space. Beginning with a linear gradation of increasing opacity from 0 to 3 to 8, this first spatial experience is intended to set a baseline for comparing translucencies. The



Exhibition view of transparency study demonstrating Weber Fechner law.



Two dimensional depth studies as per Josef Albers *Interaction of Colour.*

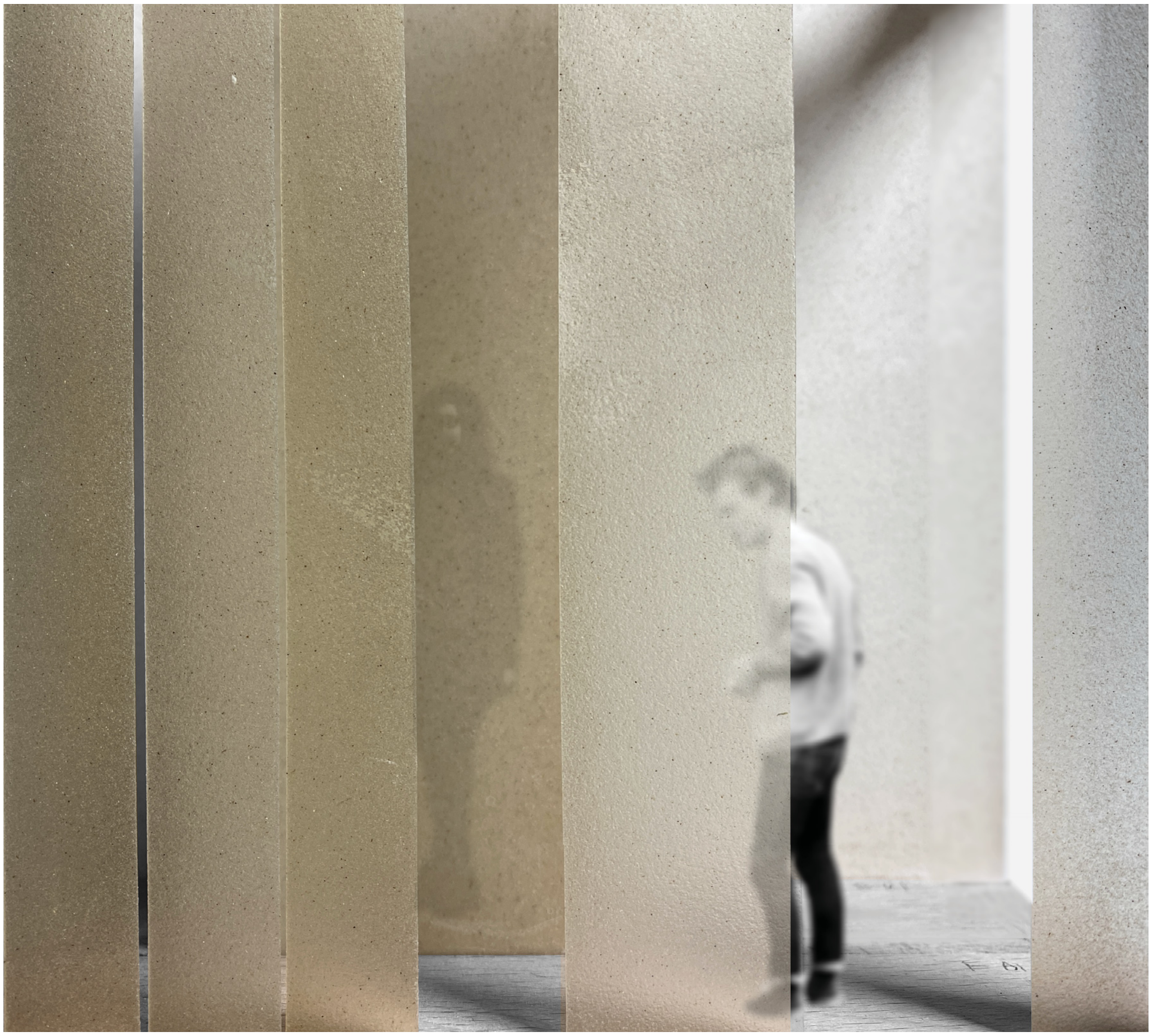


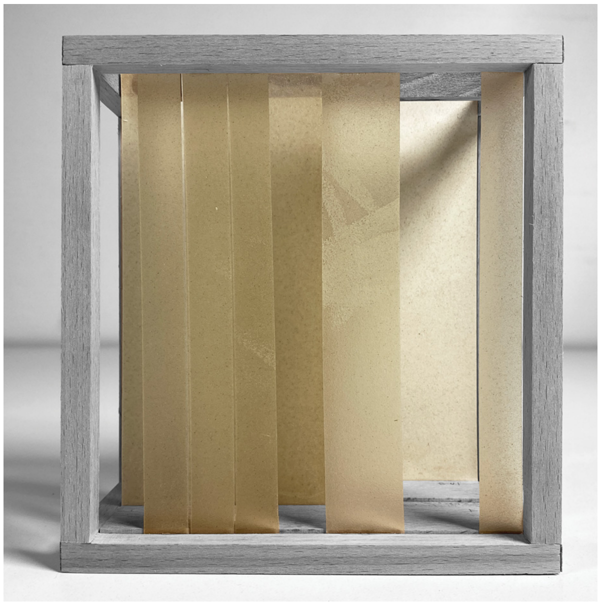
Isometric material collages paired with corresponding optical density syntax of the procession through flat panelled membranes.

gradual increases primes the viewer to perceive subtleties to come. The second experience, a stochastic constrained gradation, is a domain in which all membranes are limited to five values. The ability to sense between optical density and reflectance in this space becomes blurred. The third experience is in spatial monovalue. This experience is comprised of a single value, pushing the boundaries of the Weber Fechner Law through space. Multiple values are perceived from the layering of a single value through the augmentation of space. The final experience is in acute contrast, where two values on opposite ends of the spectrum are stochastically arranged throughout space. The heightened contrast between membranes 0 and 8 mean that perception of openings in space and super translucent membranes are perceived interchangeably.

The Structural Optics procession builds upon knowledge of visual perception developed during Modernism and extends it into a multi dimensional experience engaging environmental forces and time. The essence of this study culminates in two understandings. The first is that matter is not inert. Matter is a highly dynamic interface that is in constant response to surrounding forces, environment, time and human perception. The subleties and nuances of human perception in this interconnected web of relationships adds a layer of complexity to the experience. This installation may be designed with experience in mind, but as the viewer moves through it, their perception of it will be uniquely generated. As observed by neuroscientist Anil Seth, “We don’t just passively perceive the world, we actively generate it. The world we experience comes as much from the inside-out as the outside in, in a process hardly different from that which we casually call hallucination” (Seth 2017).

The second understanding from the study is that seemingly conflicting paradigms, Modernism and Material Ecology, informed one another in the Structural Optics study through dialogue and reciprocity. Holding past and future perspectives simultaneously marked a significant event for the author. It became a conversation that highlighted a dynamic range of approaches for working with biopolymers and visual perception in design.

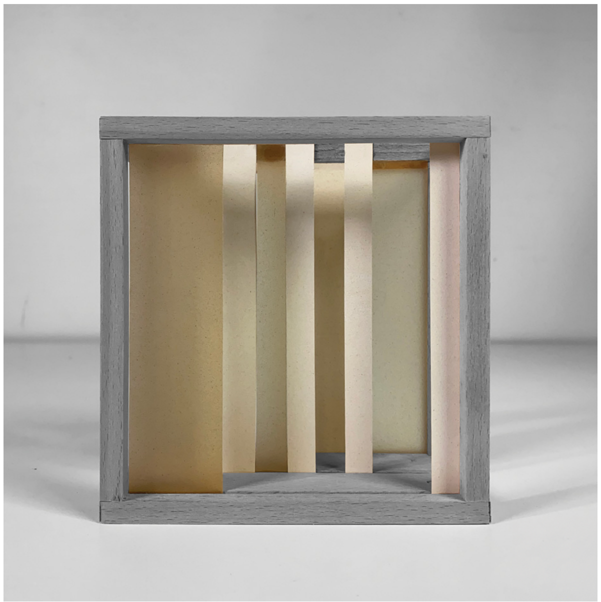




Linear gradation of increasing opacity.Image above shows inhabited experience. Image to the left shows physical model that studied optical properties of this material condition.

Stochastic constrained gradation. Image above showing inhabited experience. Image to the left showing physical model that studied optical properties of this material condition.

Spatial monovalue. Image above showing inhabited experience. Image to the left showing physical model that studied optical properties of this material condition.



Acute contrast. Image above shows inhabited experience. Image to the left showing physical model that studied optical properties of this material condition.

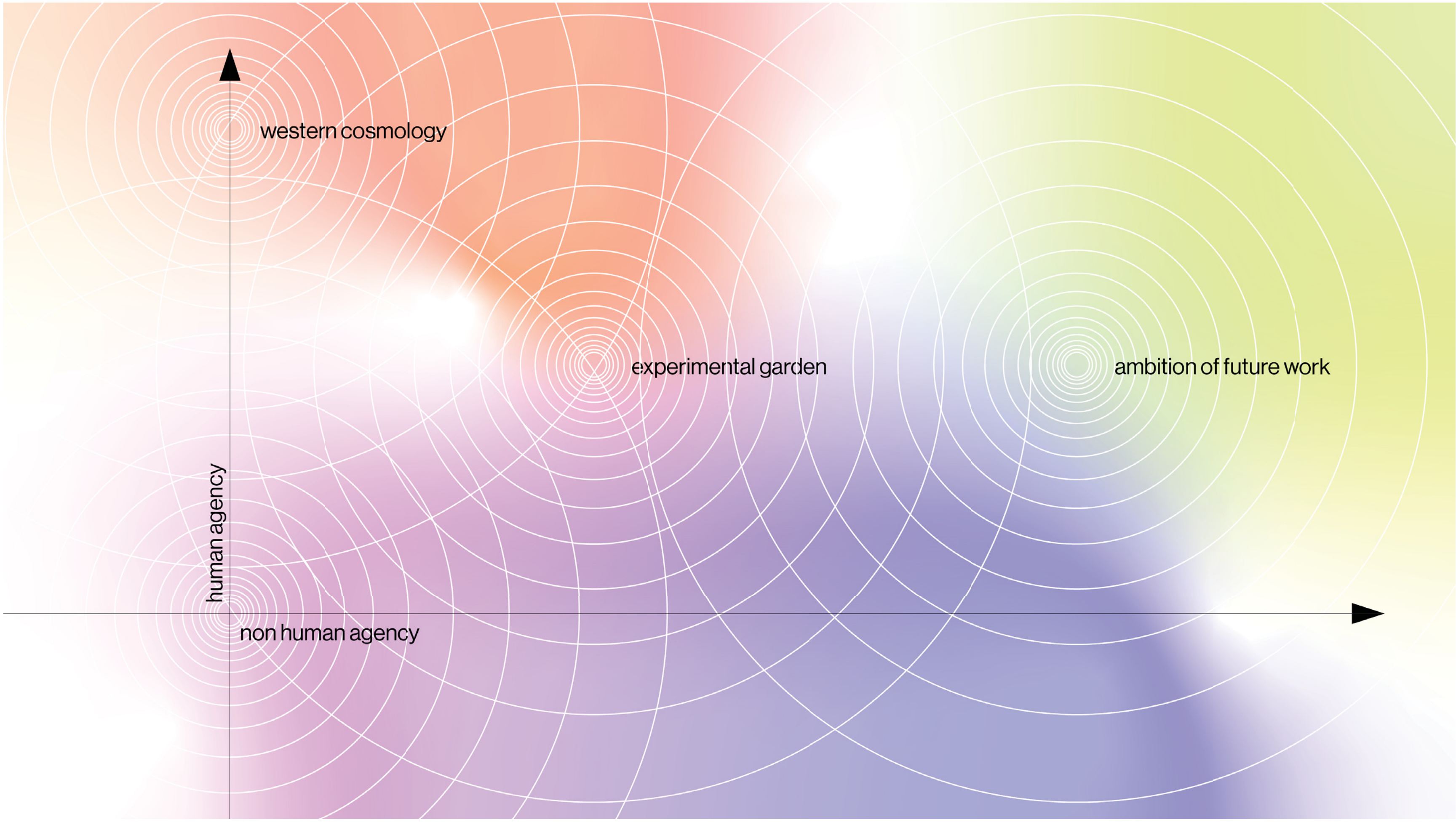
Chapter 7: Conclusion

Working with Biomaterials

Throughout the course of this thesis, I came to understand that working with biomaterials requires an agility on the continuum from human to material agency. It was important for me to understand what outcomes in this process could be controlled and at what point to let material agency take the lead. This came from a respect and reverence towards materials, knowing that they are capable of phenomenal possibilities when their rhythms are studied, within the domain of architecture and beyond. In response to the climate and ecological crises of today, biological materials and biologically informed design are becoming more prevalent within the domain of architecture. It is increasingly common for designers to delve into the transdisciplinary waters that support these types of inquiries.

Components of a Design Methodology

Expanding cosmologies and technologies are inspiring more precision in our language around the characterization of materials and perception. This thesis demonstrates how these insights can be deconstructed as components of a design methodology. Three primary components of a design methodology emerged throughout the course of this thesis may be useful for the next wave of designers looking to carry out biologically informed design. These components address methods of data collection and analysis, strategies for design and process and fabrication which together formed a proto language in this thesis for designing visual environments.



Continuum of human and non human agency.

Data Collection and Analysis

I came to understand these components during processes of reflection and conversations with my supervisor James Forren. Methodology in this project emerged as opposed to being implemented. Methodology was also something that formed a feedback loop between multi-disciplinary collaborations, primarily between oceanography, and architecture, but also touching on art and neuroscience. Methods of data collection and analysis in this research were informed by a scientific methodology and first principles approach observed while working in an oceanography lab. This included experimental design, quantification of materials through the use of a spectrophotometer, analysing data and performing a hypothesis test to either reject or fail to reject the hypothesis. Yet this methodology also laid the foundation for design synthesis. This approach called in a dialogue between design process and data collection from the very beginning. I found rapidly moving between science and design to be a generative experience. As I gained agility in this practice I was able to delve deeper into the expression of this dialogue.

The adaptation of the Munsell chart is an example of this process. The optical density data was quantified through scans on a spectrophotometer, and was expressed first in an excel generated line graph and then in a physical installation of a biomaterial matrix that is experienced at the human scale. This data is translated from objective: quantified within the domain of science, to qualitative: experienced within the domain of design. These perspectives are not mutually exclusive; they co-exist and inform one another.

Strategies for Design

The strategies for design, as demonstrated in Gradient Scales, Multi-Value Membrane and Structural Optics were all rooted in tacit material explorations. Engaging with the material without trying to impose an outcome opened the door for material agency to lead this process. However, at certain points it was crucial to make decisions in order for material studies to project into design studies. This was a process I grappled with throughout the course of my thesis. I was committed to the idea of material-driven design, but I had to define what that meant for each individual exploration. Gradient Scales explored how gradations in material at the microscale led to changes in material properties at the human scale. I chose a dynamic range of values for these gradations. Multi-Value Membrane demonstrated how fabrication could be a driving force of design development through exploring the influence of formwork on heterogenous material properties. I magnified and CNC'd microstructures with different optical properties in order to test these forms. Structural Optics was about letting go of any assumptions that had been made of the material up to that point and developing 'material sight'. In this thesis, the process of honing material sight occured through a close study of Josef Albers *Interaction of Colour.* Emergent phenomenon was observed from my perceptual senses when membranes were pared down to simple planes and relationships between values were observed. My understanding after this experience with navigating the question of material agency and human agency is that they do not exist in a binary or static state, rather as an evolving dynamic dialogue.

Process and Fabrication

The where (environment) this thesis occured in is an intimate part of the how (methodology). The projects themselves were carried out through a laboratory practice split between an architecture materials and design laboratory and an oceanography laboratory. This interdisciplinary practice created a distributed workspace designed into the thesis from the very beginning. The unintentional and unquantifiable outcomes that emerged from this interdisciplinary space involved discussions occuring in one domain often being synthesized in another. Another interesting outcome was how the underlying ethics of culturing living organisms in the wet lab informed material handling in the design lab. There is a culture of care inherent when culturing phytoplankton in which the researcher is deeply aware of conditions of life specific to the organism: nutrients, light levels and handling tolerance. This way of working fundamentally changed the way I interacted with the once living materials within my own design practice. There was an evolving translation between methods and perspectives between the domain of science and the domain of design that blurred. While I had obtained data about the optical density of the materials from spectrophotometer measurements, it was through documenting materials in different light conditions that the nuanced expressions of this optical property became clear to me. I discussed these observations with Hugh MacIntyre, and we began to parse out that these nuanced expressions were a result of not only optical density, but also reflectance. This dialogue between design and science was ongoing. A discovery in one domain often led to questions in the other.

Further, as these inquiries were driven primarily by material behavior rather than formal convention, consistant material explorations were essential in developing understandings of the behavior of material compositions. There were stages of the process that were experimental and free without being bound to a specific outcome. There were stages that were rooted in a scientific method: rigorous and repeatable. Trans scalar thinking was activated through both physical and digital modelling, and continual fabrication was a driving force of design development.

Myth of the Universal

This thesis engaged perspectives from past, present and future that formed an overarching conversation about the myth of the universal, and the ongoing evolution of this myth through modernism and into an ecological paradigm.

In 1944, Gyorgy Kepes wrote a manifesto calling for a new structure order towards a truly contemporary humanity. Kepes was writing *Language of Vision* deep in the throes of modernism where the myth of the universal was centered around a unified vision, a shared set of ideals. To Kepes, the myth of the universal was a way of uniting a collective humanity aligned with scientific progress. Influenced by Gestalt psychologists, Kepes' manifesto was radical for the time but also limited by the paradigm he sought to expand. The ways in which the myth of the universal manifested throughout the rest of the 20th century is evidenced in the proclivity towards modernism in architecture that exists to this day in both academia and practice. I am suggesting that meaning behind the myth of the universal has changed, and as such our design practices must evolve as well. As we move beyond modernism into an ecological paradigm we have the opportunity to move beyond a single vision and towards a paradigm capable of holding multiple views simultaneously. This thesis explored that non-linear space in that it culminated in a procession through biological materials that were activated by modernist modes of visual perception. The myth of the universal that is emerging alongside the Ecological Age is not new, but ancient and deeply rooted in the biological origins of life on earth.

The legacy of destructive practices towards material gain is a paradigm that western society has participated in since before the Industrial Revolution. As we stand at the threshold in time where the weight of human generated artifacts has surpassed the weight of non-human generated biomass, we hold the power to shape a material culture of the future. The experience of working with biological materials offers insights into the agency of more than human realms. I see the engagement of these perspectives as vital for designing in an age of uncertainty. Further, this thesis is situated in the domain of speculation, which enables the domain of possibility. In addition to being fully decomposable, biological materials offer opportunities for alternate paradigms of design supported by diverse myths and cosmologies. In this thesis, as in life, dynamic matter gives shape and vision to a material culture that is both ancient and futuristic, in which human generated artifacts will be continually cycled into new life.

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