Building Technology Educator's Society

Volume 2021 Article 14

6-2021

Soft Rock Studio: Exploring a “Soft Systems” Approach to “Artificial Rock”

James Forren
Dalhousie University, james.forren@dal.ca

Recommended Citation
Forren, James (2021) "Soft Rock Studio: Exploring a “Soft Systems” Approach to “Artificial Rock”," *Building Technology Educator's Society*: Vol. 2021 , Article 14.
DOI: https://doi.org/10.7275/ywvj-eg28
Available at: https://scholarworks.umass.edu/btes/vol2021/iss1/14

Soft Rock Studio: Exploring a Soft Systems Approach to "Artificial Rock"

James Forren
Dalhousie University
james.forren@dal.ca
https://orcid.org/0000-0002-6372-3615

Abstract

This paper discusses a study aimed at shifting disciplinary norms in construction materials. The study, conducted in a graduate level design-build studio, approached precast concrete construction through the lens of "artificial rock": a composite material that can use cement, sand, aggregate, and reinforcing supplements and alternatives like flax, calcium carbonate, soil, alginates, gelatin, and bacteria[1]. Taught as "The Soft Rock Studio", the course positioned artificial rock within the larger conceptual framework of "soft systems" - adaptive, networked part-to-whole relationships engaged in feedback loops with the environment.

The Soft Rock Studio designed and prototyped components and assemblies for an alignment structure – or sky room - for a coastal site. Alignment structures are landscape and architecture constructions that track the movement of the sun and stars[2].

The study design integrated empirical making, material testing and computational simulation in an iterative design methodology. The design methodology was tailored for a remote learning context and included the design and distribution of a material kit for at-home experimentation. Integrated with the methodology were process portfolios documenting student research and reflection, including responses to technology and humanities literature.

Outcomes discussed in this paper are material experimentations and iterative design possibilities of two student projects; evidence of student uptake; and reflections on the iterative design methodology. Observations and findings from alignment structure strategies are not included in the scope of this paper.

Keywords: Soft systems, Artificial rock, Natural materials, Green concrete, Materially-driven design, Morphogenetic design

Conceptual Grounding

Material-driven design (MDD) is an area of increasing research in design and architecture, intersecting the fields of process engineering and industrial design[3]. In the construction industry, new technologies in natural materials are being increasingly introduced, such as blocks formed from non-standard feedstocks like soil, urea, mycelium, and sawdust[4].

A concept like "artificial rock" can structure this changing material landscape for novice architects, assisting them in thinking through design from material production to the building assembly. The Soft Rock Studio study was built on scholarly literature in the fields of natural building materials and methods[5] and morphogenetic design theory and practice[6]. Natural building materials and methods were supported by reference literature on biomaterials[7]. Morphogenetic design theory was supported by computational design and construction methods[8].

The study goal was to shift qualitative thinking and critical reasoning around changing disciplinary norms with regards to materials. One objective was to formulate a workflow rooted in qualitative awareness and hands-on empirical feedback about materials. Awareness about industry standards, quantitative measures of durability, or liability concerns was facilitated, but the objective was not to establish new quantitative measures or demonstrate measures of code compliance for novel materials.

Artificial Rock

The embodied carbon emissions of building materials and construction represent 11% of annual global green house gas (GHG) emissions[9]. Conventional concrete production impacts the environment through air-borne carbon emissions, process energy loads, and water and sand consumption, with chief climate impacts coming from cement. Target metrics within the building sector for addressing the climate crisis are shifting from a focus on operating energy impacts to an emphasis on embodied carbon per building material unit[10]. Researchers have gone so far as to propose that an industry-wide initiative to sequester air-borne carbon in building materials can 'cool' the planet and reverse climate change impacts.

An ambition of the studio was to develop disciplinary norms of reserving cement for high-strength applications only and adapting processes of conventional concrete production for the sequestering of carbon-based biomass. In the artificial rock framework cement is no longer a central actor but is repositioned as a contingent player in a larger orchestration of ingredients.

Teaching with an artificial rock framework

Traditionally, innovation in materials and methods is reserved for shaping, joining, and assembling the outputs of material processes for producing concrete, steel, glass and timber. How might a shift in attention from operating energy to material composition in building change how we teach the materials and methods of construction and design-build?

Teaching with an artificial rock framework extends the chain of architectural innovation into designing materials and designing their performance. In addition to making decisions about a material's shaping, finish, or method of joinery, the artificial rock framework asks students to make decisions about a material's composition. They can design it to degrade, to sequester carbon, to insulate, or to be lighter. This borrows from concepts of process engineering, pairing the design and production of materials with their means and methods of construction, service life, and decommissioning.

Soft rock.

The Soft Rock Studio sought to position the instrumental framework of artificial rock within the larger conceptual framework of "soft systems", employing artificial rock tactics within the larger stratagem of systems thinking and environmental feedback loops for a holistic, iterative design approach.

In the late 1990s - as climate awareness increased in the popular imagination and the internet established networks of global interconnectivity - Sanford Kwinter described the concept of soft systems as an emerging social, cultural, and technological phenomenon. The essay called out shifts in understanding about the nature and behaviour of life forms and physical environments, and the capacities of tools and technologies to model and interact with these life forms and environments. He illustrated this concept in descriptions of interconnected global electronic networks and artificially intelligent machines as well as biological concepts of emergence, and the environmental entanglements of life forms across scales: from microbiomes to weather patterns. Kwinter described these phenomena as exhibiting a kind of softness in their function and behaviour, defining a system as “soft” when it is “flexible, adaptable, and evolving, when it is complex and maintained by a sense network of active information or feedback loops, or put in a more general way, when a system is able to sustain a certain quotient of sensitive, quasi-random flow”[11].

In articulating transcalar feedback loops – reciprocal behaviours across scales - Kwinter’s essay has helped architects think about technologies and the environment as influencing, benefitting, and drawing from each other in a biological model of interaction[12].

This lens of soft systems was explored in learning modalities of the Soft Rock Studio, such as:

- biological (as opposed to mechanical) principles of interaction explored through play and making with material kits: observing material interactions and emergent transformations
- flexible, adaptive, and evolving systems explored through material-driven iterative design methods working with the intrinsic properties of these new materials to develop flexible and adaptive forms
- system maintenance through a “sense network of active information or feedback loops” explored through computational simulation strategies to network complex relationships across different types of materials.

Research and reflection modalities based on technology and humanities literature supported the processing and translation of these experiential learning modalities, recorded in student process portfolios maintained through the term. The process portfolios provide source material in this paper for evidence of student uptake.

Soft Rock Studio study design

Material kits and biological models of design

The ambition of the Soft Rock Studio was to work with natural, regional materials: materials that were either carbon sequestering or whose growth and harvesting provided benefits to or were integrated with the regional environment.

Material kits provided to students (Figure 1) contained measuring implements, personal protective equipment, and material safety labeled ingredients. The ingredients included in the kits were bases and solvents for making biopolymer sheets and binders and aggregates to hold together with the binders. Other aggregates were added by students at home. Recipes for combining ingredients were included with the kits and identified at online resources. These recipes were curated based on their binder bases: algae (agar, alginate, carrageenan), plants (corn starch), and animals (gelatin).

The framework of artificial rock – designing at the level of composite material ingredients – required us to connect the dots between the raw material feedstock and the actual ingredients from that feedstock going into the composite materials. We had to understand what type of processing was required for that feedstock, and what the outcomes of that processing was: i.e., the building blocks students would use to make their own composite materials. For instance, one feedstock we worked with was seaweed: specifically, ascophyllum nodosum, a species commonly called rockweed This is a North Atlantic brown alga which, when broken down, can yield high levels of alginic acid to produce sodium alginate. The composites for which rockweed is a feedstock do not use the entire rockweed alga, but rather, an alginate powder extracted from the plant[13]. The powder is used as a base and mixed with water and other elements like starch, gelatin, or calcium chloride in a process of chemical bonding called cross-linking. These crosslinked matrices can also form mechanical bonds with aggregate materials like sawdust or ground shells. All of which can be linked back to the living environment they are brought from and which they will return to.

This biological model of design relies less on observing the mechanical interaction of two elements of the same material, and more on the convergence of two dissimilar constituent materials into a resolved material whole: recognizing that convergence as part of a larger "living" system. This is captured in the reflection of one student working with the material kit: "… what's most interesting to me in this material [sawdust / damar resin] is that it is composed of two very different materials from two very different trees. The tree is the feedback loop, meeting another tree and creating a rock-hard little puck. I hope it decomposes one day and becomes nutrients for more plant or organism life, a never-ending feedback loop"[14].

Figure 1. Material kit contents distributed to students.

The process of conceiving and creating these new material composites was described as a sequence of material flow from 1) *raw materials*, or material feedstock, from the region (seaweed, seashells, shellfish, grasses, agricultural waste) to 2) *material extracts* that are by-products of the processing of raw materials (such as flax shives or flax fibers from flax plants, alginates from seaweeds, chitin and ground up shells from mussel and oyster shells, and gelatin from animal by-products) to 3) *composite building materials* produced by combining material extracts.

One issue the studio wrestled with was the scalar translation to full scale building materials. Some materials for use in construction, such as biochar, chitin, and cement, were not able to be worked with at home due to university health and safety regulations. In some instances, students speculated that the material kit-produced composite could perform as an actual building material. In other instances, students were asked to research a larger scale corollary for their material kit-produced composite.

Material-driven iterative testing supporting flexible, adaptive, and evolving systems

Kwinter's essay identifies the biological theory of "epigenesis" – a process through which cells divide and self-organize through interactions between in-built codes and environmental factors - as a model for the growth and emergence of "soft systems". The process of "morphogenesis" – the steps by which organizing cells assume a form or shape – is a subcategory of this epigenetic framework noted by Kwinter and has become a mode of analogical reasoning in design theory[15]. This concept of morphogenesis and theories of morphogenetic design were drawn upon as a guide for structuring students' design imagination.

Morphogenetic design concepts are akin to industrial design and engineering approaches of material-driven design (MDD)[16] and emphasize form-finding through empirical experimentation and play. Experimentation leads to discovering and working with intrinsic material properties to find out what the material "wants to do". From this discovery methods of form-making and strategies of building performance are explored which work with or amplify these intrinsic properties. Common characteristics shared by morphogenetic design methodologies include designer evaluation of intrinsic material properties, primarily through qualitative empirical testing and / or quantitative measurement. Through the outcomes of this testing designers hypothesize on component morphologies: the shape of things and how they can be tethered to, informed by, and driven by the intrinsic properties identified. Morphogenetic design proposals work with such intrinsic properties as the anisotropy of rip-sawn timber[17], the hygroscopy of maple veneers[18], or the elasticity of textile weaves[19].

The qualitative model demonstrated in the studio was most closely related to theories and methods developed by Tim Ingold and distinguished primarily between the concept of form imposed on matter – or hylomorphism - and form arising from matter – or morphogenesis[20]. This is an iterative model using qualitative assessments and process refinements which, in some instances, translated to quantitative measures and decision-making.

Computational simulation strategies supporting system maintenance through a "sense network of active information or feedback loops"

To further develop part-to-whole relationships and a flexible and adapting network of components, students were introduced to computational methods of networking assemblies: specifically, techniques of discrete aggregation through Grasshopper for Rhino with discrete aggregation plug-ins Wasp and Fox; and adaptive form-finding physics solvers RhinoVault and Kangaroo and curvature analysis protocols. They also learned techniques to bring physical outcomes into the computer through methods of photogrammetry.

This modeled the action of orchestrating feedback loops of active information. The software models part to whole relationships, and the feedback between micro-scale formal decisions and mezzo-scale configuration outcomes. Simulation platforms like physics solvers further orchestrate these feedback loops by introducing an external force, like gravity. And the method of photogrammetry facilitates a digital-physical feedback loop in the design methodology.

Knowledge gained from material studies.

Working from morphogenetic design principles, students played with materials (Figure 2), reflected on their findings, and then developed more precise tests to develop control and mastery over their composite materials. Playing with the materials revealed which were brittle, which were elastic, what their workability times were, and how factors of temperature and humidity affected them: weighing the pragmatics of how to work with a material alongside the imagination of what these materials could do. Here we discuss the outcomes of playing, reflecting, and refining through two student projects' material studies, emergent design properties from these studies, and exploration of these properties in design.

Figure 2. Select outcomes from initial material kit experiments.

Study group 1

The material experimenter from study group one worked from a set of recipes of various bases using an aggregate of sawdust. Their experiments began by seeking a certain degree of dimensional stability and reliability.

Initial studies with the sawdust and bases of agar agar and damar resin achieved a certain level of dimensional stability. However, the blocks were also “flaking woodchips everywhere”[21]. This ultimately gave them the idea of designing blocks that would decay and host life or provide nutrients in an environmental feedback loop; a concept they would carry forward in their design process.

They then tried other materials to try and develop a dense, dimensionally stable material. They experimented with eggshell aggregate composites using bases of calcium carbonate with water and calcium carbonate with calcium alginate and water. These turned out to be ”brittle, chalky and very fragile”[22]. They then experimented with a new base - sodium alginate, water and vinegar – and added mussel shells to the aggregate. This had better binding properties, holding the composite together and withstanding impact and tearing tests. The student researcher returned to just the eggshell aggregate, but with the sodium alginate, water & vinegar base. This withstood numerous impact tests, including with a hammer. The students as a group then distinguished their material experiment outcomes on a spectrum of porosity and looseness at one end and rigidity and density at the other: a dual hierarchy of porous to dense and loose to rigid.

Along the spectrum of porous to dense and loose to rigid, group one polarized these values to make a loose, porous block and a dense, rigid block, experimenting further with different mixtures before settling on agar / corn-starch composite mixture of sawdust for one and ground eggshells for another (Figure 3).

Figure 3. Compressive blocks of eggshell and agar agar (left) and sawdust and agar agar (right) in preliminary wedge-shape form with interlocking key.

Study group 2

The material experimenter in study group two worked repeatedly with the eggshell composite recipe of ground eggshell aggregate with a calcium carbonate and water base - examining the effects of different types of molding on the material. Like the experimenter in study group one, they found the composite to have promising compressive strength, but problems with dimensional stability and brittleness. Also, like study group one’s researcher they experimented with supplements to correct the dimensional instability and brittleness.

The supplements they added sought more reliable bonding by modifying the aggregate mixture, not the carbonate base. The aggregate additions were clay, mussel shells, ground rice, and ground pistachio shells. Although the additives of pistachio shells and rice were non-regional improvisations, the student researcher proposed them as stand-ins for potential further research and development with locally available supplements. In their own words: the ground rice was added “to help stabilize the material during the curing process with its starchy polymeric-carbohydrate structures and [improve] moisture retention … as a stand in for a locally sourced starch”. The ground pistachio shells were added as “an alternative to starch as the water retaining material, with a molecular structure built up of layered triglycerides and cellulose that can be sourced from food waste”[23].

Figure 4. Four eggshell and calcium carbonate tiles with (clockwise from top left) 1) ground pistachios, 2) ground rice, 3) clay, and 4) ground mussel shells.

These additives had the desired outcome of more cohesive units; however, dimensional stability was not resolved as the tubes and tiles made from these materials warped while curing (Figure 4).

Emergent design prospects

Study group 1

The emergent design prospect from group one's stable and degradable blocks was creating a system where "some materials will degrade, while others will remain intact for a longer period" to "challenge a typical building life, death, and rebirth cycle … degradable falsework can support the structural assembly during construction, and then either be reused as falsework in other areas of construction or slowly degrade into a detached material to be applied in new ways, such as mulch for planting beds … leaving only the structural elements behind".

This binary was 'programmed' into the assembly through a unitized, aggregation strategy to create spans, voids, and degradable regions. In a geometric packing-scheme of equilateral square pyramids, each pyramidal unit's material composition reflected its role in the structure (falsework or spanning). Falsework blocks (sawdust and agar agar) were planned to aide in the structure's assembly, but to dissolve over time to allow targeted openings to emerge in the structure, with new organisms hosted on the sawdust remnants on the structure and below it. Spanning blocks (eggshell composite) carried loads in a friction-fit packing configuration (Figure 5).

Figure 5. Equilateral four-sided pyramid packing structure of degradable (brown) and structural (white) composite blocks.

These materials represented corollaries for scalable applications: eggshell composite represented oyster-shell concrete mixtures and sawdust blocks simulated mycelium as a degradable component. (Neither lime (for the oyster shell concrete) nor mycelium were allowed to be worked with at home). Both full scale materials (oyster shells and mycelium) could be harvested near the proposed site, "reducing the ecological impact and benefiting from materials that could be seen as biological waste" [24].

Study group 2

Through iterative testing of different component morphologies - tubes, beads, and tiles – study group two tried to achieve predictable outcomes for a vaulted structure. After several failed attempts, they recognized that the synclastic curling of their tile components could mimic and marry to the synclastic curvature of a vaulted geometry, "working with [rather than against] this material's expression to warp and deform"[25].

This new approach required them to find "a way of calculating and predicting the degree and extent with which this material warps and deforms … [to] design with this material property, and design with a clearer more predictable outcome"[26]. With this goal in mind, they developed a bi-directional physical-digital pipeline. From one end, they created a method of measuring physical outcomes using a photogrammetry routine. The resulting photogrammetry point cloud was then translated to a vector based NURBS surface. From this surface they then calculated a degree of curvature for the physical tile.

From the other, digital, direction of the physical-digital pipeline site, view, and pathway parameters were used to determine edge curves for a vaulted shell. The shell was generated by a physics solver. The shell's curvature was then evaluated in rows along the vaulted surface. These curvature values were subdivided into four ranges, each corresponding with an average curvature range of one of the four physical tiles. Then these tiles of pistachio shells, mussel shells, clay, and rice were mapped to specific areas of the shell based on their curvature: their geometry attuned to their material composition (Figure 6).

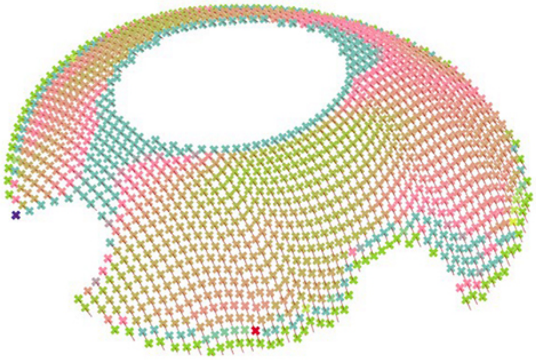

Figure 6. Analysis mapping tile curvature of clay (green), mussel shell (cyan), pistachio (pink), and rice (brown) tiles to vaulted shell.

Evaluation of the iterative design approach

As a holistic methodology, investigating intrinsic material properties informed reciprocal material relationships between form and place: such as utilizing a material for formwork which can return to the earth; or letting the innate curvature of materials from the site inform the shape of a structure. The students' conceptual frameworks evolved from inherited perspectives of deploying available materials, to tuning materials for specific design effects and thinking through the chains of custody. This represents a fundamental shift in disciplinary norms in the teaching of means and methods of construction. Threading together steps from raw materials to material extracts, to building materials the kits, the design method, and the computational tools, challenged students to think up and down this chain of custody from extraction to formulation, to installation, and decommissioning. Not in a linear progression, but in a nonlinear, reciprocating relationship across multiple scales.

This transcalar framework provides novice architects with a method for thinking through micro and macro materiality. At the level of material extracts students are making decisions about the micro-level of composite constituent materials. Once they develop a full building assembly, they are engaging material at the mezzo-level. And as they consider chains of custody beyond the site and beyond the construction assembly, they are entering into macro-scale material considerations.

Two general trends were observed from the two study group investigations. First, each design response can be described as an emergent strategy of multiple composites working together in an interdependent network, each performing a different function. This was expressed as an aggregation of equilateral square pyramid-shaped voxels in study group one: each unit performing as either fixed or degradable. It was expressed as a form-found, minimal bending tile vault in study group two: each unit assuming a different degree of curvature based on its location along the shell.

Second, the projects demonstrated a position with regards to time. Study group one focused on the longitudinal time frame of materials coming from the site to build the structure and returning to the site as the structure decays. This was expressed as each pyramid-shaped unit was assigned either a short or long time scale as either falsework or structure. Study group two focused on a shorter time frame between component formation and curing. Their time basis was also worked into a computational process as a record of curvature of individual tiles.

Conclusion

This effort to shift disciplinary norms required us to shift our expertise and expand our notion of means and methods of construction. Teaching students about composite "ingredients" diversified our disciplinary collaborations by engaging a process engineer and permaculture expert. And it asked us to educate ourselves on methods of harvesting, procuring, and processing materials, and develop ideas on how to enter into these supply chains. Classically developed strategies and concepts around innovation – such as 'intervention' – served as a road map for navigating this new territory. An intervention seeks to understand a process, and then hypothesize where to intervene, where to innovate and adapt. But rather than inserting a novel piece of hardware, a non-standard method of planing wood or casting concrete, or a computer-numerically controlled machine, the artificial rock method explored inserting a new chemical compound, a different processed mineral, or a batch of starch or cellulose.

A corollary classical strategy, what we might call "emergence", served us on the other end of that process: observing the outcomes of an experiment and hypothesizing how these outcomes may themselves intervene on a design process by seeing the inconsistent curing of the composite tile or flaking of a block as a design opportunity.

Expanding our sense of technology education also brought to the fore questions around the ethics of this new approach. As we seek to shift disciplinary norms on what can be considered a building material, how might we negotiate a changed landscape where seaweed, for instance, becomes an industrialized resource? Modern-era industrial models of resource extraction – which can leave an ecosystem ravaged and depleted - run counter to the ambitions of natural building construction to preserve, renew, and remediate natural and social environments. Here concepts of "permaculture" – such as regenerating feedstock sources and building sustainable social infrastructure – can serve as a corrective to conventional extraction methods.

The reflective modalities of the course afforded students the opportunity to process and verbalize this type of speculation. For instance, one student wondered in their process portfolio, "if how we are looking at the Earth is unknowingly holding us back from seeing things from new perspectives that could change the damaging planetary dynamics we are currently engaged in, how do we begin to relate to life differently so we can orient towards regeneration and the dynamic flow of energy happening all around us all the time" [27]?

As part of this reflective modality, students were asked to place their future selves – as leaders within the built environment – in a position of agency with regards to materials, and ask themselves, what might new ways of thinking about materials mean for the role of the architect. One student's response was, "I see the role of an architect to go beyond designing a building, but to engage with the design of the systems that create and inhabit our buildings. This brings into consideration where does the scope of any particular project lie, and where are the boundaries of the systems of people, materials, and energy that create our buildings"[28].

This uptake in expanded disciplinary agency reflects our capacity as educators to instill skills of stewardship, agency, and innovation in novice architects. To provide frameworks for thinking deeply about the composition of materials, for developing adaptive material formulations, and for networking those solutions with the environment using available technologies.

These skills enable them to become critical agents within emerging fields of material innovation, positioning them as critical thinkers about what is going into our buildings, how our buildings can serve multiple functions: as carbon sequestering biomass and a place to live; as a source of soil nutrients, and host for living organisms: in short, activating the agency of materials.

Acknowledgements

This work is supported by the Canadian Precast / Prestressed Concrete Institute (CPCI).

Consultants to the studio: Aaron Outhwaitte, Ph.D. cand., Dalhousie University; Kim Thompson, Executive Director, the Deanery Project; Charles Williams, the Deanery Project; Dave Chapman, Fellow Royal Astronomical Society of Canada (RASC); and Sebastien Sarrazin (M.Arch. 2020).

Material kit, course, and technology design, development, and production by research assistants Alexander Crosby, M.Arch. 2021 and Andrew Gilmour, M.Arch 2021, Dalhousie University.

Student projects and process portfolios executed by M.Arch. 2022 students: Sara Bajelan, George Grant, Michael Harvey, Kevin Mockford, Laure Nolte, Branden Schick, and Rita Wang with additional support by Larissa Korol, Brittany Letwin, and Brayden Wesley.

Description of ascophyllum nodosum and biomaterial binders provided by Alexander Crosby and Aaron Outhwaitte. Description of agar corn starch composites provide by Laure Nolte.

Notes or References:

---

1 Fernando Martirena and Paul Jaquin, " Concrete: The Reinvention of Artificial Rock," in *The New Carbon Architecture*, ed. Bruce King (Gabriola Island: New Society Publishers, 2017), p 69-84.

2 Deborah Scherrer, *Ancient Observatories: Timeless Knowledge*. (Stanford: Stanford University Solar Center, 2018), p 3

3 Elvin Karana, Bahareh Barati, Valentina Rognoli, and Anouk Zeeuw Van Der Laan. "Material driven design (MDD): A method to design for material experiences," *International Journal of Design* Vol. 9 No. 2 (2015), p 35 to 54.

4 Bruce King, *The New Carbon Architecture : Building to Cool the Climate*, (Gabriola Island: New Society Publishers, 2017), p 83 to 84.

5 John Fernandez. *Material Architecture.* (Hoboken: Taylor and Francis, 2012), p 245 to 262.

6 Sanford Kwinter, ”Soft systems.” In *Culture Lab*, ed. Brian Boigonm (Princeton Architecture Press: New York, 1993), p 207-228.

7 Dr. Alysia Garmulewicz and Liz Corbin. "Nature’s Recipe Book", May 3, 2021, https://materiom.org/.

8 Block Research Group, “RhinoVAULT 2”, May 3, 2021, https://www.food4rhino.com/app/rhinovault-2; Petras Vestartas, “Fox”, May 3, 2021, https://www.food4rhino.com/app/fox.

9 Thibaut Abergel, Brian Dean and John Dulac, “UN Environment and International Energy Agency: Towards a zero-emission, efficient, and resilient buildings and construction sector, Global Status Report 2017”. International Energy Agency (IEA) for the Global Alliance for Buildings and Construction (GABC). (2017) Pg 14.

10 Bruce King, "The New Carbon Architecture," *Building* 68 (2) (Apr 2018): 38-39.; Chris Magwood. *Making better buildings: a comparative guide to sustainable construction for homeowners and contractors*. (Gabriola Island: New Society Publishers, 2014), p xvii to xviii.

11 Kwinter, "Soft Systems" p 211.

12 Joseph Dahmen, "Soft futures: mushrooms and regenerative design," *Journal of Architectural Education* 71, no.

---

1 (2017), p 57 to 64; Lola Sheppard. "From site to territory," *Bracket 2: Goes Soft* (2013), p 179 to 184.

[13] Dennis J McHugh. "Production, properties and uses of alginates." *Production and Utilization of Products from Commercial Seaweeds. FAO. Fish. Tech. Pap* 288 (1987): 58-115. http://www.fao.org/3/X5822E/x5822e04.htm

14 Student process portfolio.

15 Michael Weinstock, “Morphogenesis and the Mathematics of Emergence,” In *Computational design thinking*, ed. Achim Menges and Sean Ahlquist. (John Wiley & Sons, 2011).

16 Karana, "Material driven design (MDD)”, p 35 to 54.

17 Anders Holden Deleuran, Martin Tamke, and Mette Ramsgard Thomsen. "Designing with deformation: sketching material and aggregate behaviour of actively deforming structures." In *Proceedings of the 2011 Symposium on Simulation for Architecture and Urban Design*, (2011), pp. 52-59.

18 Achim Menges, and Steffen Reichert. "Performative wood: physically programming the responsive architecture of the HygroScope and HygroSkin projects." *Architectural Design* 85, no. 5 (2015): p 66 to 73.

19 Daniel Baerlecken and Katherine Wright Johnson. "Nominalized Matter-Generative Textiles Procedures." *SIGraDi 2013 [Proceedings of the 17th Conference of the Iberoamerican Society of Digital Graphics,* (2013), p 515 to 519.

20 Tim Ingold. *Making: Anthropology, archaeology, art and architecture*. (London: Routledge, 2013).

21 Student process portfolio.

22 ibid.

23 ibid.

24 ibid.

25 ibid.

26 ibid.

27 ibid.

28 ibid.