FOREGROUND FOR MOSSES:

DESIGNING 3D PRINTED CLAY BRYOBRICKS TO ENHANCE THE BUILT ENVIRONMENT

HEATHER R. TIETZ
Master's Project
University of Oregon
Master of Landscape Architecture

June 10, 2021

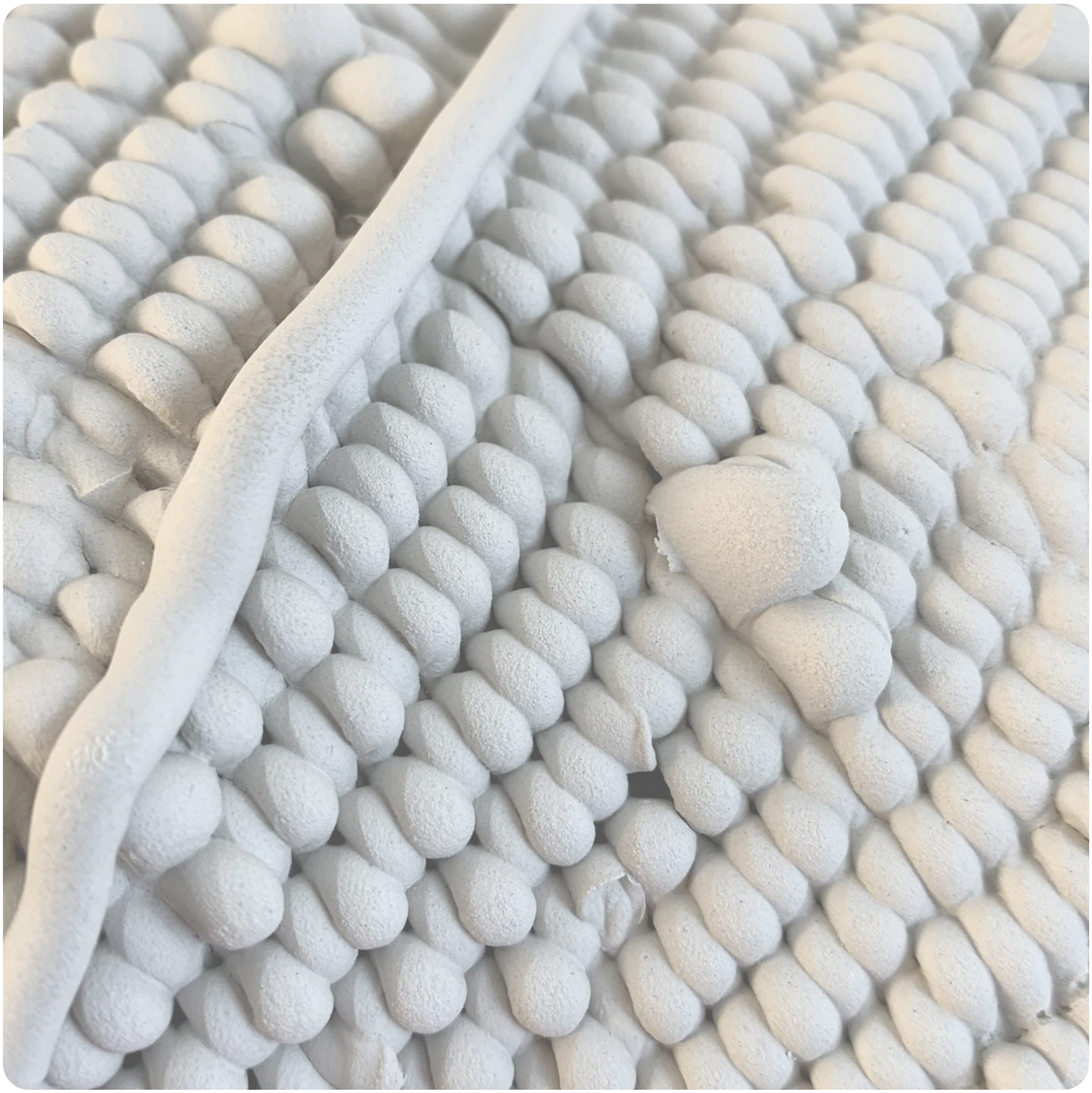


Fig. ii. Collapsed clay print.

TABLE OF CONTENTS

Fig. iii. First print.

LIST OF FIGURES

Contents

Fig. iv. Barnacle interface clay print.

ACKNOWLEDGMENTS

While this work is called my Master's Project, all facets of this project were possible only through the insight, assistance, and enthusiasm of many people and organizations included in mentions here and beyond the acknowledgments. Thank you for believing in this work and for your support across the last three to ten years.

David Buckley Borden for design insight and encouragement during weekly conversations, and overall guidance for this Master's Project.

Robert Gusek for assistance with setting up the printer remotely and sharing code. Without your help, this project would not have been possible.

Michael Geffel for leading an inspiring studio on Experimental Gardens and for Jun Hak Lee with opening the conversation to ideas for designing with mosses.

Ignacio Lopez Buson and Mary Polites for guiding me in the design process in a contextualized and responsive approach and for your support and enthusiasm.

Stacy Jo Scott for advise on exploring materiality in clay and workflows for using the printer.

Logman Arja for teaching about weaving patterns and for giving me access to the Potterbot for testing more complex designs.

Bruce McCune for helping me identify, observe, and harvest mosses and for the guidance along the way. Janice Glime for sharing ideas on moss propagation and support for this work.

Jeffrey Garman for enthusiasm with setting up the Raspberri Pi for capturing a time lapse of the main experiment.

Aman Agrawal for sharing the gcode script in Grasshopper for a direct printing process.

Maria Coronado Carrera and Mark Fretz for going out of your way to help me track environmental conditions and visualize the data.

Kurt Langworthy for graciously giving me access the imaging and microscope equipment at CAMCOR.

Zack Smith for firing the experiment interfaces to cone 7 and for sharing about creative exchange.

FMI Truck Sales and Services and the Urban Farm for the space to set up the experiments.

The Fuller Center for giving me access to a wonderful studio space when access to any space was very limited this year.

Aaron Woolverton for your guidance in approaching many aspects of this project and in your companionship.

Mom for your constant support.

Fig. v. Home experiment, interior view.

APPROVAL PAGE

DESIGNING 3D PRINTED CLAY BRYOBRICKS TO ENHANCE THE BUILT ENVIRONMENT

by

Heather R. Tietz

....

Chair:

David Buckley Borden

Committee Members:

Chris Enright

Kory Russel

Submitted in Partial Fulfillment for the Master of Landscape Architecture

Department of Landscape Architecture
College of Design
University of Oregon 2021

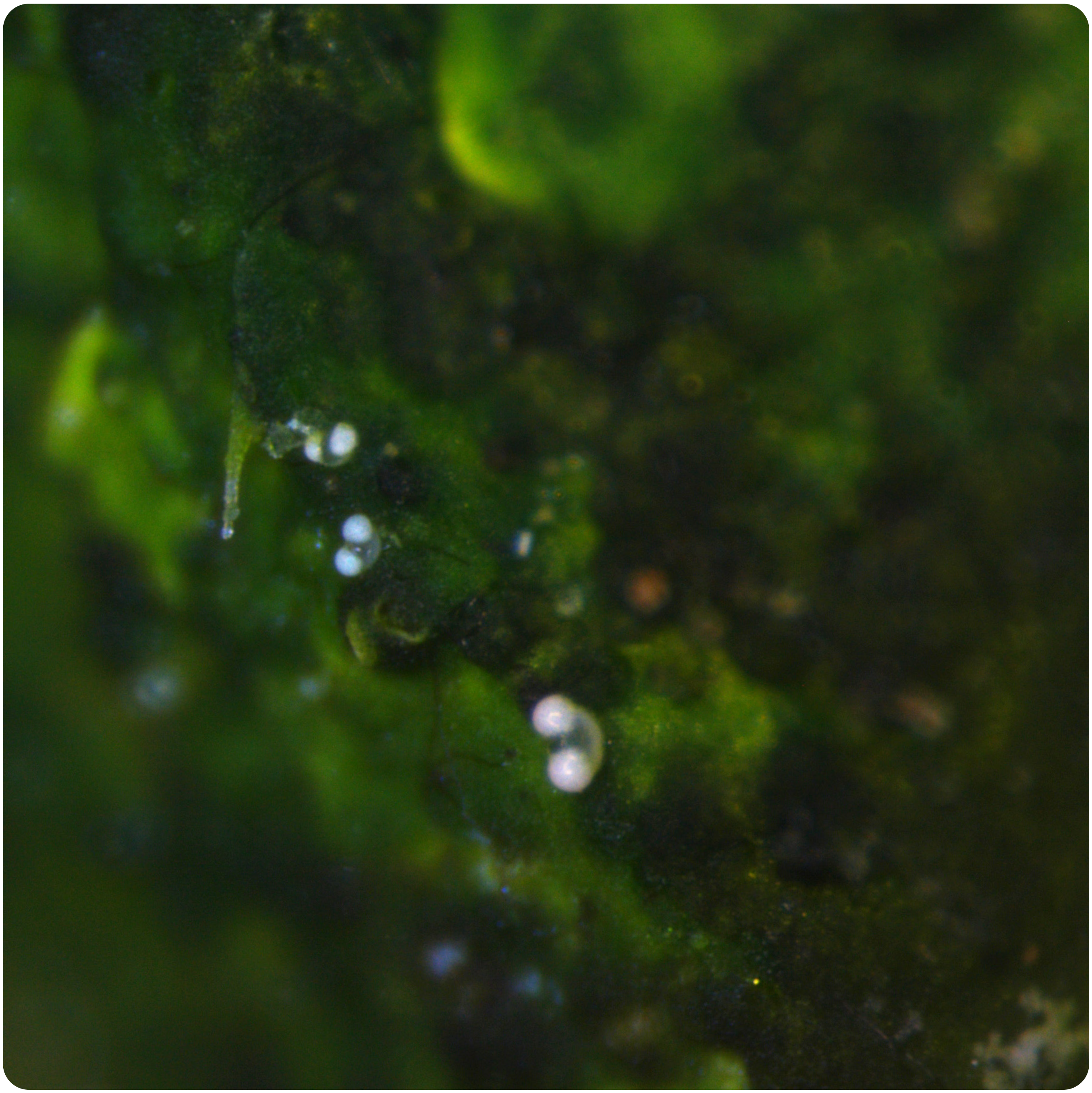
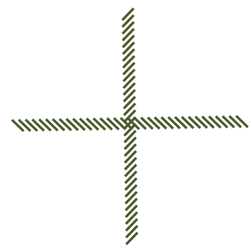


Fig. vi. 53X amplification, top view of protonema growth and pollen grains on ceramic substrate of process piece from home experiment.

ABSTRACT

This project explores the potential between the ecological services of mosses and designed ceramic substrate for creating ecologically enhanced landscapes. Communities and environments are negatively affected by areas with impervious surfaces and pollution. The efficacy of new typologies in landscape architecture, such as living walls, could be improved with mosses' ecological benefits and resilience. Clay is an abundant resource that can be reshaped utilizing 3D printing and support the propagation of mosses. This research-through-design approach interrogates the potential growth of mosses vis-a-vis experiments in 3D clay printing to create optimal substrates. The experimental design was installed in four locations testing four unique substrates against moss growth. For the three-month duration of the experiment, monitoring through rephotography, a hygrometer, and written observations tracked responses to environmental conditions. Experimental results informed a framework designing with mosses and a rapid prototyping process using an advanced 3D clay printer to develop a modular screen system. For the final design phase, the forms were simplified and contextualized at Lawrence Hall at the University of Oregon as a speculative case study. Experiments that received more irrigation and less solar exposure exhibited more moss growth. This research, experiment, and subsequent design work serve as a proof of concept for designing with mosses and clay using emerging technology for creating performative landscapes.

Common Green Infrastructure	*Emerging Green Infrastructure*
	
Vascular Plants	Mosses
Introduced Plants	Native Plants
Plastic-based	Local Clays
Impervious	Porous
More expensive	Less Exposure
Chemical Producing	Nature-based
Space-Intensive	Space-Efficient
Retrofit-Heavy	Retrofit-Less
High-Weight Load	Low Weight-Load
Heat Generation	Heat Mitigation
Particulate Stasis	Particulate Collection
High Maintenance	Low Maintenance
Limited Surface Potential	Surface Potential
More Irrigation	Little Irrigation

CLIMATE CRISIS
URBAN HEAT ISLAND
POLLUTION MITIGATION
INEQUALITY IN URBAN ENVIRONMENTS

Fig. vii. Comparisons between traditional vertical and green wall infrastructure and moss and ceramic integrated system.

BRIEF INTRODUCTION

Problem Statement

In landscape architecture, designers typically design with non-local materials and vascular plants. Urban spaces are negatively affected by pollution, the urban heat island effect, and the lack of green space contributing to the degradation of the surrounding environment and communities.

Sub-Problem Statement

Emerging typologies of plant-integrated infrastructure such as green roofs and living walls are largely ineffective because of their high cost, high production of synthetic materials, and significant failure rates. Vascular plants are commonly used in these urban applications and do not perform well in extreme conditions.

Research Question

How can we optimize the benefits of mosses by using innovative technologies such as 3D printing to design ceramic substrates to effect positive change in the built environment?

Sub-Research Questions

Research: What are the benefits of mosses and ceramic material, and how can we integrate them into the built environment?

Experiment: Will mosses grow on clay or ceramic 3D printed substrate in Eugene, Oregon?

Rapid Prototyping: Through rapid prototyping using 3D printing, which forms and material compositions in ceramic or clay are optimal for facilitating moss growth?

Design: How does a 3D clay printed vertical system prototype look?

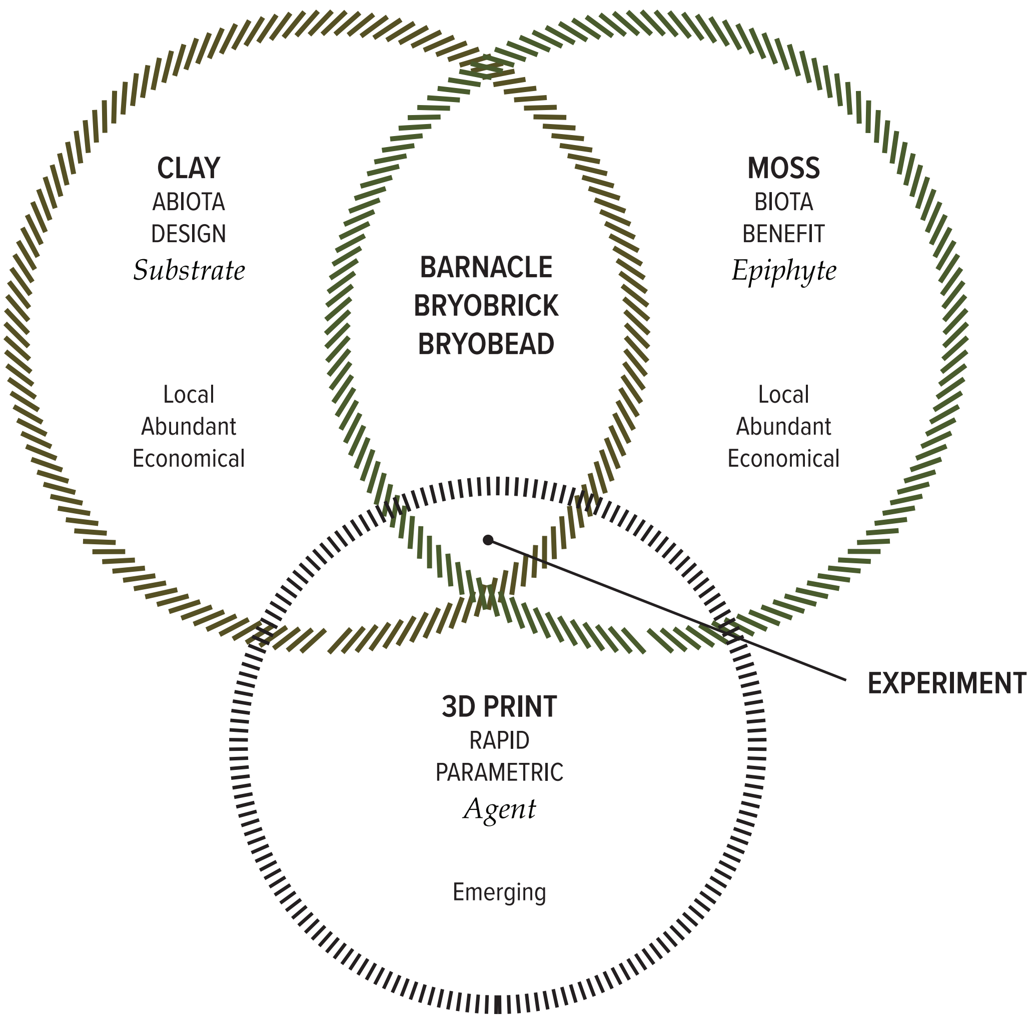


Fig. 1.0.0. Definitions. Designing for moss and clay through the rapid prototying process of 3D printing has lead to the development of the experiment in the form of barnacle interfaces, bryobricks which compose the modular screen system and bryobeads which compose the columnar bryobead

INTRODUCTION

Designing in landscape architecture holds significant potential as it involves shaping the outdoor environment at the intersection of the arts and sciences. In recent years, emerging methodologies in the field, such as research-through-design, have opened the possibilities for understanding and investigating processes and interactions of the landscape across scales. The method of research-through-design involves background research, responding through iterative design, and provokes more questions.

Our collective choices impact our environment by altering ecological systems and continue to exacerbate the climate crisis. As designers working in the landscape as ecology, it is essential to ask questions about the changes we wish to make with resources we have access to through data, tools, and educational resources. Studying landscape architecture in the Pacific Northwest of the United States presents a unique opportunity to address ecological questions in design through a particular lens of examining the interaction of climate, plants, and materials.

The geological and ecological history of the Willamette Valley appears in the region's increasingly diametrical climate of rainy winters and dry summers. Rich soils from the deposition of the Missoula floods and clays from the Mt. Mazama volcanic eruption host many resilient native and introduced plants and animal life. Among the plant life, poikilohydric mosses grow abundantly on natural and synthetic substrates in the wet winter and spring and dry out in the summer.

Mosses are unique for their small growth size up to 10 cm tall, high surface to mass ratio, and high absorption rate. Their single-celled structure lacks roots, flowers, and fruits allowing mosses to absorb moisture and nutrients primarily through the leaf's exposure to the air. Moisture must be present to facilitate photosynthesis and reproduction. Recent studies have shown that mosses are effective biomonitors, proficient at nutrient cycling, prevent erosion, are fire retardant, and offer many additional benefits.

An identifiable gap exists in the possibilities of designing with moss in the built environment due to the lack of research and design of moss applications. In landscape architecture, practitioners designing with plants have typically studied plants' identification and design use that have a meaningful spatial and visual impact, including trees, shrubs, ground covers, and flowers. In places where mosses grow abundantly, such as in the Pacific Northwest, mosses have been less explored in professional landscape designs. However, mosses have been recently introduced into garden design through DIY approaches, leaving much to explore moss propagation and design applications.

Over the last fifty years, new typologies of landscape architecture have emerged, including living walls, green roofs, and deck parks due to an increased awareness of climate change. These design approaches on retrofitted and new infrastructure often include ecological benefits of adding green space for visual pleasure, reducing and filtering runoff, and creating ecological microrefugia to offset the Urban Heat Island effect. These design initiatives are essential, but questions remain about their endurance, success in the establishment, and high production cost due to their heavy reliance on design with vascular plants. There is potential in pushing the boundaries of these typologies to include cryptogamic cover such as mosses at the intersection of landscape architecture. Lack of understanding of mosses' propagation has led to the perception that mosses threaten buildings by eroding substrates, leading to regular maintenance removal, especially in the United States. Western cultural attitudes towards mosses may also reflect messiness and lack of care. Bruce McCune, Bryologist at Oregon State University, holds that mosses only erode or destruct surfaces when vascular plants grow with mosses, using the leverage of stored water within the plant to pry materials apart (https://mosslandscapes.weebly.com/moss-roofs.html). In Asia, mosses have been a valued component of gardens for hundreds of years and are encouraged to grow on objects in the garden.

Designing with mosses includes considering and understanding the substrate material, application methods, environmental conditions, and selected species. These variables present exciting experimental potential for design using the research through design methodology. Designing the substrate material to inform the spatial pattern and arrangement of the moss is a control to explore in real-time and on-the-ground through subjective or objective inquiry. Clay is a suitable material to explore as a substrate medium for its malleable, abundant, and affordable qualities. In addition, clay has a rich cultural history of use for artistic expression and functional applications in the built environment in planting pots, pavers, bricks, and roofs. With new technology such as 3D printing, clay holds potential for being shaped in complex and controlled ways.

Pairing clay as a substrate material with moss for propagation through the process of 3D printing and experiment holds the potential to create new typologies in landscape architecture as seen in Figure 1.0.0. Mosses grow well both on rigid substrate and soft substrate if the surface is relatively rough, allowing rhizoids to attach, situated in low-light, and provides a porous texture for moisture collection. The malleable clay structure allows for custom formation into suitable spaces on varying slopes, aspects, and sized areas creating hyperfunctional living objects with mosses. For example, opportunities for growing moss on clay or ceramic substrate would function well near rain gutters and drains, tree grates, and public transportation infrastructure. Mosses currently thrive along the edges and grooves of infrastructure in the built environment and could enhance forgotten spaces through design. Scaling up the design intervention of mosses across the matrix of the urban environment could effectively create a positive impact when applied on larger scales.

Fig. 1.0.1. Collage demonstrating the importance of moisture exchange for mosses.

1. AIM

My aim for this Master's Project has been to accomplish several goals that extend from the research question; "How can we optimize the benefits of mosses by using innovative technologies such as 3D printing to design ceramic substrate to effect positive change in the environment? Naturally, within this question, many sub-questions have been addressed at different phases of this work. The main components of this project include research, applied methodology, experiment, rapid prototyping, peripheral design explorations, speculative design, and final design work. This project work expands on area-of-concentration classes taken during the MLA program, which include Digital/Analog Ceramics, Independent Studies in Ecology of Mosses, Grasshopper, Research Methods, and Topics in Design Development (3D Printing).

The work is foregrounded in research that seeks to understand the elements of the project (see conceptual diagram in Figure 1.0.1). Conducted research generated insight into designing with mosses to shed light on their structure, lifecycle, benefits, and historical uses. There are many benefits and scientific data that demonstrate the unique qualities of mosses that give clues about their potential benefit to design. Research on defining clay and ceramic material elucidates the structural qualities. Historical and modern applications and creative techniques share the rich intersection with culture and expression. Research on 3D printing, 3D printing with clay, digital design, and bio-design show unique interrelationships and how the advancement of technology has informed the built environment. A survey and highlight selection of case studies offer a foundation for this design work from the precedents covered in this research.

The methodological section examines approaches to design in landscape architecture. Due to the varied phases of this work, there are intersections with additional research by design approaches as defined in Nijhuis and Bobbink, Lenzholzer's, and Deming and Swaffield's writing. Because this work is highly responsive to the work generated previously, it is primarily abductive and constructivist. The experiment phase generated the bulk of the design and lessons learned defined in the methodology section.

Within the research-through-design framework, I experimented with 3D printed clay and ceramic interfaces to better understand designing optimal substrate systems for moss propagation. Inherent to setting up the experiment, a rapid prototyping phase ran concurrently with forming design concepts and learning digital tools. The concepts, preparation, and technological approaches during this phase were documented. The Main part of the experiment was tested in a residential space on a deck in Eugene, Oregon. Three other satellite locations included a residential property on a patio, the Urban Farm near the railroad at the University of Oregon, and an industrial area on West 11th in Eugene, Oregon. The timescale of the experiment was completed within three months, so documented changes were limited to within the time frame.

Throughout the experiment, the changes were analyzed through field notes, photographic documentation, remote sensing, and a time-lapse camera. The locations were also analyzed for their solar radiation and sun-hour exposure. Prior to setting up the experiment, ideas for further applications in the landscape were considered. During the monitoring and observation phase of the experiment, ideas formed towards further applications of how future applied designs might be successful. The experiments were analyzed through a meta-analysis compared to each other and generally as a whole during the process discussion to generate a design framework for the design development of moss and prospective ceramic work.

For envisioning future work, rapid prototyping was used again to test design ideas for the landscape. This work was enhanced through the use of a more advanced 3D clay printer which allowed for designing more significant and more complex geometries. This work interrogated the potential of a rain screen and led to the speculative design of a bryobrick screen. Midway results from the experiment were considered in the design development for this work. As a tangent to rapid prototyping, the method of coil-building was integrated with research on the history of ceramics and digital design to create a potentially stackable brick. This work was scanned with a camera to create a mesh and processed through a mesh-building program.

The final design integrates learned feedback from the various parts of the project. The benefits of working with moss and clay were affirmed through research that this approach would have an environmentally enhancing benefit.

The process of rapid prototyping was adapted that considered the limits of design modeling and tools. Results and analytical tools generated from the experiment were folded into the design work of the Lawrence Hall courtyard. The final work expanded on the horizontal surface of the ground, from the vertical surface of the screen to the three-dimensional space of a bryobead matrix.

The process work was on view through a co-organized exhibition entitled “Foregrounding.” It was essential to show this process work through talking about the process and showing the visual work in person. Through a slideshow, a time-lapse of the experiment showed change over time. Sharing information about the benefits of mosses, the abundance of clay, and the advantages of digital design can inform and enhance landscape architecture. Through testing and responsive design, optimal design prototypes for mosses within the built environment can be more accurately articulated. With further testing and applications, exciting new typologies may emerge and hold the potential to benefit the places where we live and to leverage the spaces that are currently underutilized, forgotten, or out of reach.

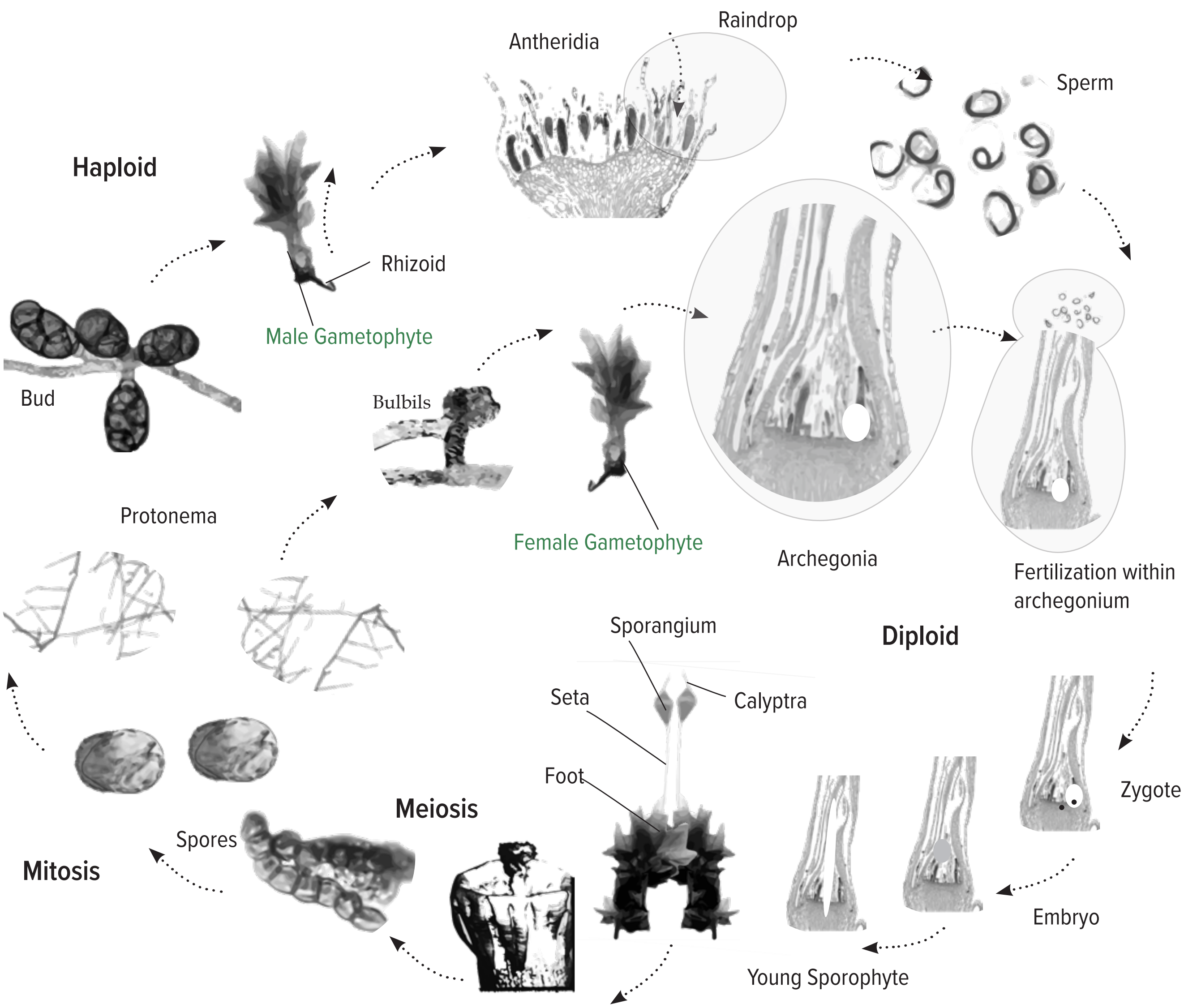


Fig. 2.0.0. The gametophyte of most mosses may reproduce asexually via gemmae in gemmae cups, bulbils budding from gametophyte surfaces, or from fragmentation of the branching protonema. Lifespan typically ranges from two to ten years.

2. BACKGROUND

2.0 MOSSES

The etymology of moss is derived from the prefix bryo-, meaning moss in Greek. Mosses were some of the first plants to colonize the land 350 million years ago during the Devonian Era and now are the second largest group of plants with 22,000 species worldwide. (Kimmerer, 2020; Chairunnisa and Susanto 2018). Mosses are commonly overlooked as they are small in scale and virtually impossible to identify without the ability to observe mosses under a microscope, so most mosses do not have common names (Kimmerer 2020). However, mosses are integral to the function of the forest and become successful working with natural processes on surfaces. Where dominant plants are too large to live in a space, mosses grow. Due to their low competitive ability, they live within interstitial spaces and do not grab resources efficiently, living off few nutrients. Because they can live with limited resources, they can be considered generous plants offering significant contributions to ecological processes. If moisture is available for reproduction, mosses are opportunists and grow on synthetic and natural surfaces in many different environments.

Included in the Bryophyte category, mosses, liverworts, hornworts share similar characteristics as seen in Figure 2.0.1. Mosses lack flowers, fruits, seeds, roots. They are cryptogamic meaning that their sexuality is hidden. Their lifecycle alternates between the haploid gametophyte for sexual reproduction and diploid sporophyte reproduction as seen in Figure 2.0.0. Mosses tend to produce only sperm-organs or egg-organs at one time to promote genetic variation. The female structure for making eggs is the archegonium. The antheridium are sausage-like and are for sperm production. Both the archegonium and antheridium are usually grouped and exists within the leaves as perichaetia. Moisture is needed for the sperm to swim with two tails towards the egg in the bottle-shaped archegonium nestled within the lower leaves. When the egg and sperm merge, they form a zygote, and the diploid phase begins the growth of the sporophyte. The developed spores are supported by a seta. The brown capsule shoots sperm out of the capsule that is opened by the operculum. The spores develop into protonema, the first stage of growth where the moss appears like algae and is filamentous. Buds appear on the filaments that allow the gamete's green shoots to grow, and the cycle continues. Mosses have root-like structures called rhizoids which assist in the attachment to the substrate. The other reproduction method of mosses occurs when specialized structures detach due to fragmentation. Through the dispersal of wind and water, a new plant will emerge if conditions are suitable. Mosses range in their lifecycle from one to ten years.

Robin Wall Kimmerer beautifully shares in "Gathering Moss" that "Every element of moss is designed for its affinity to water". Pleurocarpous mosses grow the sporophyte along the branches of the moss, and acrocarpous mosses grow the sporophyte at the terminal tips as seen in Figure 2.0.3. The growth pattern of the sporophyte informs the shape of the mosses, with pleurocarpous mosses growing prostrate branching and fragmented in their growth patterns. Acrocarpous mosses tend to grow more upright, tolerate more light, and in mounding patterns. Their leaves range in shape from dentate, serrate, and ciliate. The mosses possess positive and negative charges which attract water to any side of the one-celled thick leaf. Their leaves overlap, form accordion folds, possess concave pockets, or tiny bumps (papillae) with the goal of trapping water. Their height can reach .4 to 4 inches, with the largest and more rare species reaching 20 inches growing within the boundary layer of low airflow. When mosses dry out, their leaves shrivel and often spiral to hold water and when moistened, bend towards the light (Kimmerer 2020).

Mosses can be evaluated and integrated into many different types of climates for their performance as mosses grow in almost all regions worldwide (Spitale 2020). Understanding how levels of evaporation and precipitation have led to the development of moss communities, it is possible to reference how drought-tolerant species reveal past climatic and hydrologic regimes (Glime 2007). The only environments that mosses are unable to tolerate are salty (Kimmerer 2020). Mosses are resilient to a wide range of temperatures and exposure to pollution (Julinova and Beckovsky 2019). Suitable to wet and dry climates, mosses are unique for their desiccation tolerance and poikilohydric properties, meaning they photosynthesize in high moisture or overcast conditions. They slow metabolically without access to moisture and are active when other plants are not in similar conditions (Julinova and Beckovsky 2019; Proctor 2009; Goffinet and Shaw 2009). Ideal conditions for growing moss

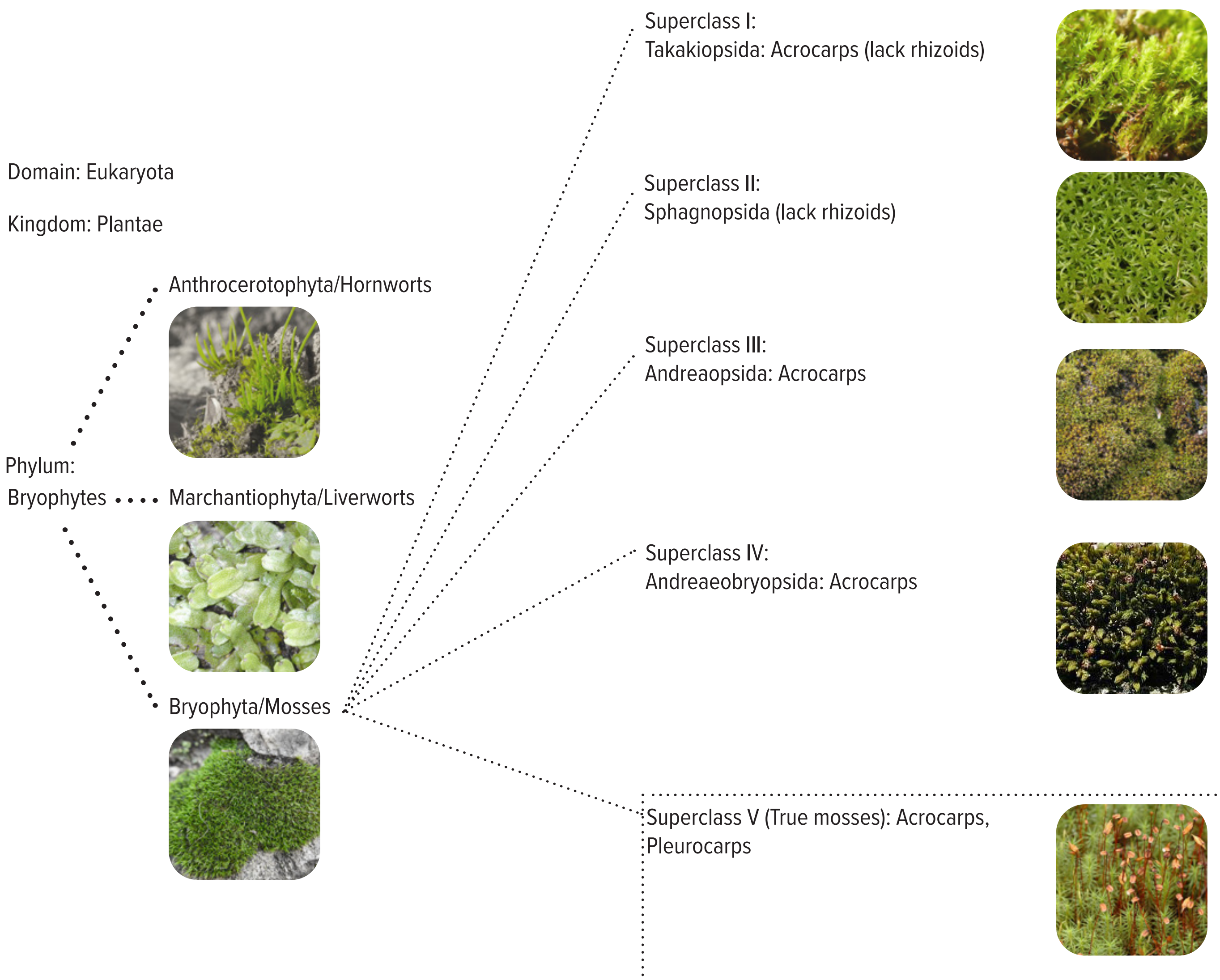
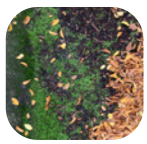
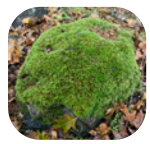


Fig. 2.0.1. Classification of Mosses in Flora Community



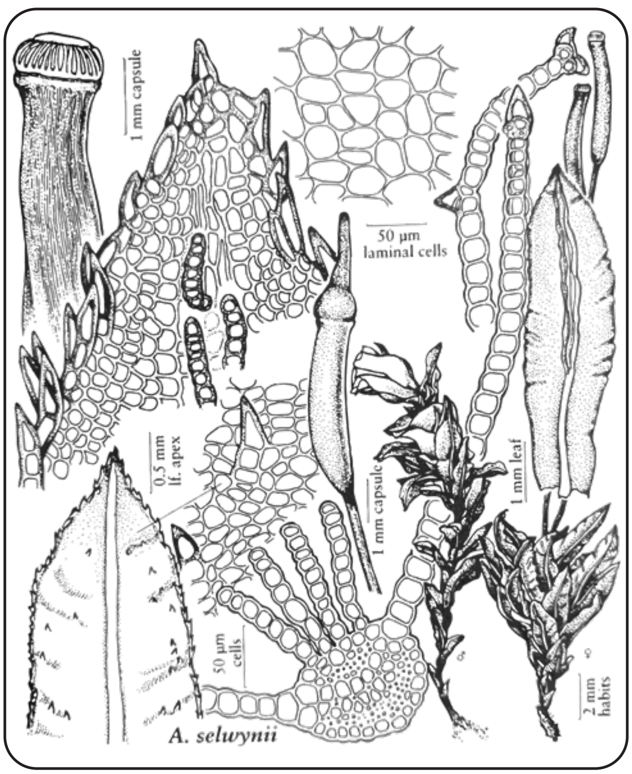


On Soil → Unfired Clay

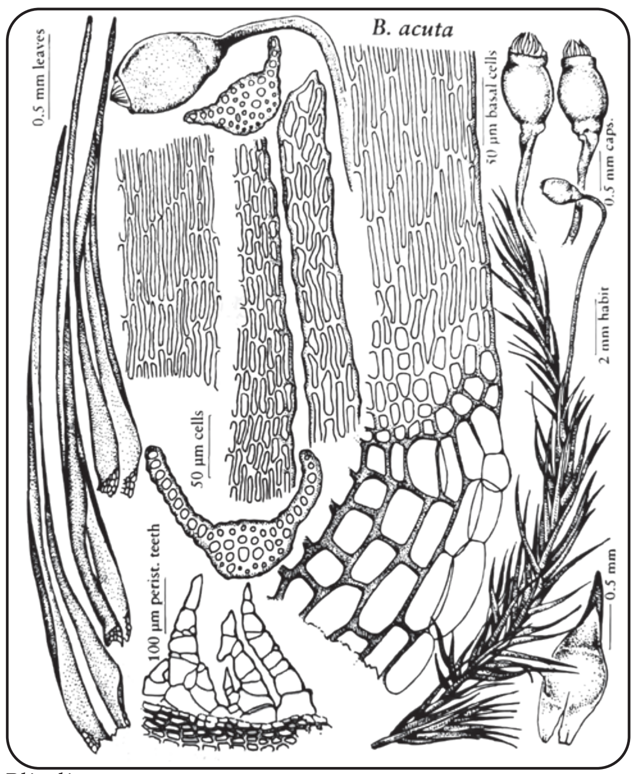
Atrichum selwynii, Brachythecium asperrimum, Eurhynchium praelongum var. stokesii, Hookeria lucens, Isopterygium elegans, Leucolepis menziesii, Mnium spinulosum, Plagiomnium insigne, Plagiomnium venustum, Plagiothecium denticulatum, Plagiothecium laetum, Plagiothecium undulatum, Pogonatum aplinum var. sylvaticum, Rhizomnium perssonii, Rhytidiadelphus triquetrus

On Rock → Brick (Fired Clay)

Amphidium californicum, Amphidium lapponicum, Barbula vinealis, Bartramia pomiformis, Blindia acuta, Cynodontium jenneri, Grimmia torquata, Heterocladium macounni, Rhacomitrium heterostichum



Atrichum selwynii



Blindia acuta

Fig. 2.0.2. Substrates that mosses grow in humid transition zone of the Pacific Northwest. *Atrichum,* illustration, pg. 152, *Flora of North America.*

are temperatures between 15-25 degrees Celsius and full sunlight intensity around 70,000-1000,00 lux (Richards, 1984). Typically, mosses grow best on slightly acidic surfaces with a pH between 5.0 and 5.5 (Chairunnisa and Susanto 2018).

Mosses have been studied under a range of conditions and exhibit certain unique qualities which make them ideal for further testing on a ceramic substrate. Mosses prefer access to fewer nutrients than most other plants (Bates 2009). Because mosses have small, flexible structures and lack significant vertical height nor weight, they grow well in small spaces with textured surfaces that lack nutrients. Compared to lichens, their close relative, mosses, perform better in the dryer and hotter conditions than other plants, especially in comparison to vascular plants (de Guevara 2018). Due to their poikilohydric nature, they can resume photosynthesis and metabolize within five to twenty minutes of being rehydrated (Kimmerer, 2020). Mosses exist in a critical region called the biocrust or boundary layer, where they serve as a buffer between air and soil and grow to about 1 cm tall on average (Cheng 2019). Within this layer, airflow is relatively still, which allows them to retain moisture. If mosses grew above this boundary layer, they would lose their moisture with the wind and dry out, so the boundary layer essentially determines their height (Kimmerer 2020). The liminal zone of biocrusts is vital because this is an area where plants can protect their substrate from erosion, other plants and filter pollutants. (Cheng 2019; Rosentreter 2019). It has been noted that mosses can contribute to acidification in the soil and atmosphere by releasing the hydrogen cations they store while taking up calcium, magnesium, and sodium (Goffinet and Shaw 2009; Glime 2007). Mosses grow on several substrates, both natural and artificial, and could be tested for their growth on a ceramic substrate (Hylander 2015). Figure 2.0.2. to the left shows this potential.

Mosses are mainly known for their biomonitoring properties and ability to filter pollutants (Gonzalez, Petrosky 2014; Goffinet and Shaw 2009). Mosses have a significantly high surface area to mass ratio, enhancing their ability to absorb moisture and collect pollutants (Proctor 2009). As non-vascular plants without flowers, root systems, and channels for moving water, their one-celled leaves are flexible and will shift their structure to absorb a range of particle sizes (Goffinet and Shaw

2009; Capozzi, 2018; Peck 2006). In their dry state, they can absorb surrounding metals within five minutes of exposure and absorb up to 16-26 times their weight (Gonzalez and Petrovsky 2014). In a recent study, Sphagnum palustre was exposed to plastic nano-particles and was absorbed into the non-growing areas of moss over three weeks and remained within the cell structure after heavy washing (Fig. 2) (Capozzi 2018). In Portland, Oregon, moss bags were placed at strategic locations around the city and near industrial sites. Their ability to show pollutants within a tiny timeframe mark mosses as significant indicators in their absorption of heavy metals (Gonzalez and Petrovsky 2014). They are the most efficient and economically plant with the highest performance of biomonitoring pollutants and inspired the Clean Air Act in Oregon (Goffinet and Shaw 2009).

Not only will mosses collect pollutants and serve as a biomonitor over time, but mosses can also be indicators of climate change and reveal environmental conditions (Ochoa-Hueso 2011). Terrestrial mosses have long been recognized as major actors in global climate feedback and local nutrient budgets (Rennie 1810). Mosses absorb various types of nutrients from different surfaces, ranging from dry and wet materials (Goffinet and Shaw 2009). Oliver Gilbert, a Bryologist in England found that Grimmia pulvinate responded to SO2 and interrupted distribution, reproduction, and capsule formation (Glime 2007). Mosses facilitate biomineralization within their cells and have been known to accumulate the properties that compose opal minerals within their non-growing plant cells (Goffinet and Shaw 2009). Copper mosses such as Mielichhoferia elognata have been used for mineral prospecting in marine areas, and copper values have been reported with 30-700ppm of copper (Glime 2007). Beyond absorbing and growing minerals within cell structures, mosses are known to filter carbon and nitrogen. Many mosses harbor cyanobacteria and convert this to atmospheric nitrogen that can be taken up by other plants where nitrogen is otherwise limited (McCune, Whitbeck 2021). Moss mats in forested areas account for one-fifth of all net carbon uptake and more than half of nitrogen fixation in boreal forest understories and filter particulates before reaching the soil (Lindo et al. 2013; Goffinet and Shaw 2009). Nutrients assimilated into mosses may be released through decay or during significant rain events (Coxson 1991). Feather mosses have significant landscape nutrient effects

Fig. 2.0.3. Morphology of Mosses, http://flora.huh.harvard.edu/FloraData/001/WebFiles/fna27/FNA27-1-Morphology.htm Flora of North America. Accessed 10/30/20

Fig. 2.0.4. A collage showing ecological connections with fauna through habitat, food, and transportation.

for fixing nitrogen, and carbon fixation in moss mats is about 20% of all understory net primary production (Hasselquist et al. 2016).

Mosses require moisture for higher metabolic processing and possess properties for filtering water on preferred substrates. Their dense, overlapping leaf arrangements and absorbent structural properties make mosses one of the optimal plants for holding water in equilibrium with their environment and exhibit turgor in saturation where other plants are more fragile (Proctor 2009). They are ectohydric in nature, meaning they allow liquid to move along their surfaces freely with surface tension and slow run-off (Proctor 2009). Bryophytes also act as sinks for water and nutrients in intercepted stemflow and throughfall (Goffinet and Shaw 2009). Mosses are known to grow in areas where there are grooves and texture in the furrow of trees or cracks in sidewalks as this is where moisture collects and serves as an optimal surface for moss propagation. Mosses can live on various substances such as tree trunks, dead wood, weathered wood, soil, and rocks (Windadri 2009; Grdovic and Stevanovic 2006.) Mosses have adapted to live with relatively low light at 5% of available ambient light for photosynthesis. Their chlorophyll balance has an adjusted pigment balance and a modified photosynthesis pathway (Kimmerer 2020). Interestingly, when exposed to light intensity, mosses can increase their saturation points when higher carbon dioxide levels are available (Julinova and Beckovsky 2019).

Bryologist, Robin Wall Kimmerer, has shared that mosses are the “coral reef” of the forest because they provide habitat for many organisms living within and on their structures. One gram of moss provides habitat for 132,000 tardigrades, 15,000 protozoa, 3000 springtails, 800 rotifers, 500 nematodes, 400 mites, and 200 fly larvae (Kimmerer 2003). Alaskan reindeer, bison, wooly mammoth, peary caribou, birds, squirrels, mice, lugs, and ants eat the mosses’ sporophytes. Marbeled murrelets and the picaflor rubi use mosses as a nest. Papuan weevils transport mosses on their backs. Slugs have assisted in increased germination rates in comparison to the mosses reproducing by spores only. Ants in Sweden have been recorded to transport the gemmae of Aulacomium androgynum over four hours of movement. Other insects and critters such as spiders, earthworms, and birds have assisted in the great dispersal of mosses as seen in Figure 2.0.4. During short times, humans have added mosses to bread dough to act as a filler. Moss parts have been found in the digestive tract of a human living 5000 years ago. Mosses additionally support plant growth; in Nova Scotia Polytrichum assists with the germination of (White Spruce) Picea glauca, and in prairie soils where roots tend to grow more profound beyond the water absorbent properties of the mosses, plants are assisted in their growth. Heather, licorice fern, and infant trees establish better in environments where mosses grow (Kimmerer, 2003).

Mosses play an essential role in rural environments, and harvesting methods should be carefully considered to protect ecological habitats. Mosses in boreal forests are known for their water balancing, erosion control, nitrogen budget, and habitat for many organisms (Hylander 2005). Sphagnum mosses are known for their use as a soil amendment for various reasons from their potential to increase soil structure and aerate heavy soils (McCune and Whitbeck mosslandscapes.weebly.com). Due to the mosses' high rate of cover, they may reduce the intrusion of nonnative grasses (Rosentreter 2020). For commercial purposes, mosses harvested in the Pacific Northwest are typically collected in abundant in low elevation areas and along creek beds on federal lands such as national forests (USDA FS 1969; Peck 2006). Harvested mats can be as large as 100 cm3 in volume and up to 1000 cm3 and a small clipping is shown in Figure 2.0.5. (Peck 2006). Once mosses are harvested, vegetative cover on average grows in 50% of the area over ten years of growth. When moss fragmentation occurs due to harvesting, mosses will reproduce asexually (Buck 2006). Ideally, mosses should be harvested within the top third to half to preserve their vegetative structure (Buck 2006). Rotation periods for harvesting is recommended to be between 15-25-year periods (Peck 2006). Steps have been taken to limit commercial harvesting on old-growth forests (Peck 2006). More data is needed on the impact of harvested moss, renewability, or impacted species and social and economic aspects.

Mosses have been part of traditional garden designs for hundreds of years and serve as metaphors for the passage of time, longevity, mortality, and many aspects of the human condition. Garden art was introduced to Japan

Fig. 2.0.5. Mosses a few days after collection showing signs of drying while stored in paper bag. These mosses were collected on a rooftop near Corvallis, Oregon for fragmentation and application of experiment.

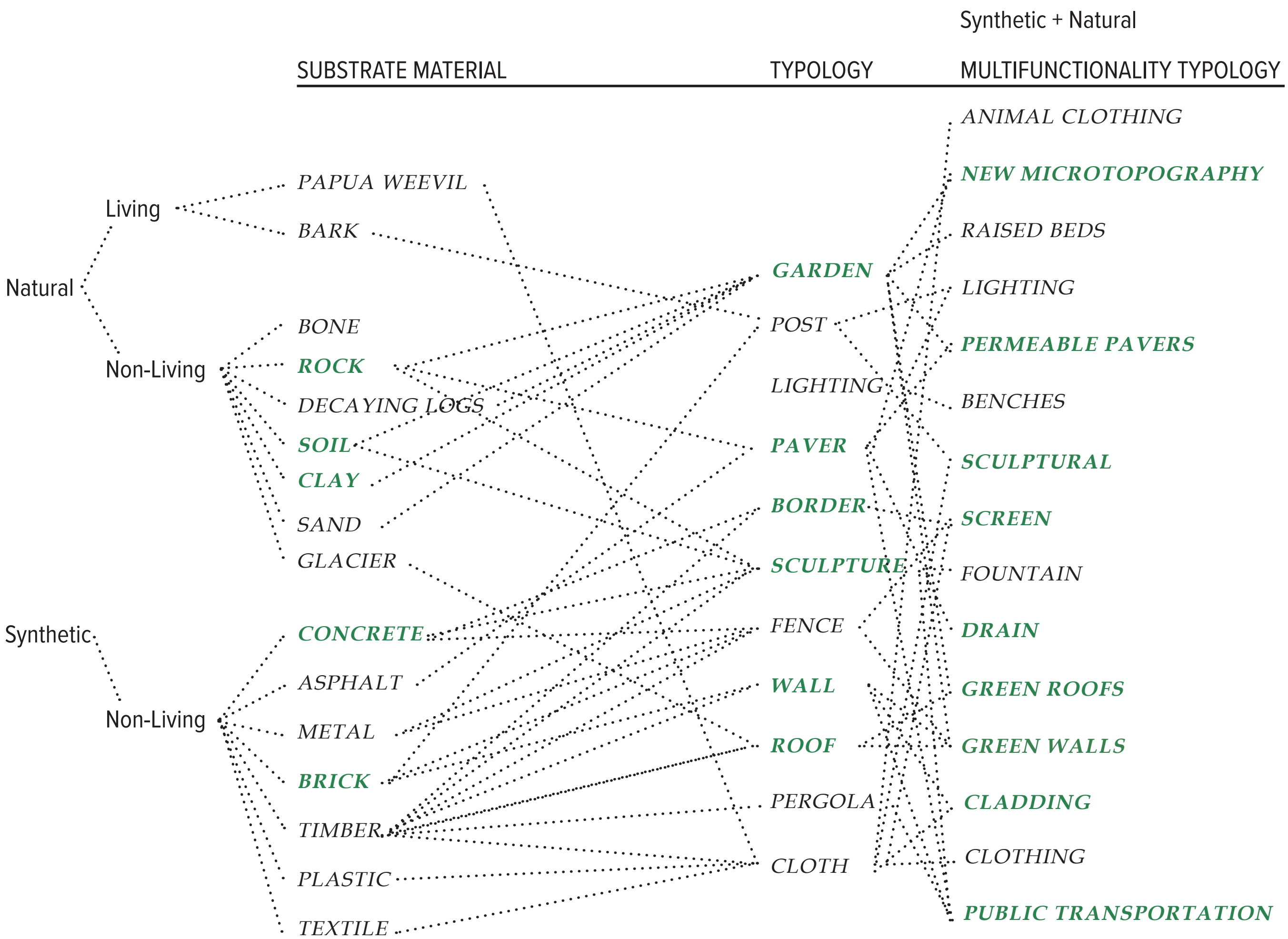


Fig. 2.0.6. Drawing connections between synthetic and natural materials on which mosses grow and potential typological integrations.

from China and Korea by foreign craftsmen during the Nara Period of 710-794 CE and dates as far back to the early gardens of religious sites during the Jomon Period of 10,000 BP. At Saijo-ji, known as the Kokodero, a moss garden with over 120 mosses and temple species in Kyoto, Japan dates to the Nara Period. The garden is known for the beautiful moss covering the garden and has been hitherto emulated in Japanese gardens. In the 20th Century, Mirei Shigemori revitalized the art of the Japanese Garden and contributed to its renewal. His approach to design sought to connect tradition with modernity concepts and in the exploration of memory. In his early masterpiece at Tofuku-ji in Kyoto, the Hasso no Niwa (Garden of Eight Views), he reused cut stones to depict a grid pattern in a plane of moss in 1939 (Tschumi 2006). The abstract stone stetting serves as a recall of the priest's childhood and serves as a place memory.

The perception of mosses in gardens and the built environment in the west have primarily been disliked. In the Pacific Northwest Plant Disease Management Handbook published by Bruce McCune, Bryologist and Kristen Whitbeck, a former postdoctoral researcher at Oregon State University, explain the negative perception of mosses in the Pacific Northwest (McCune, Whitbeck mosslandscapes.weebly.com). Mosses have been misunderstood in their ability to break down substrate material, a primary reason why they have not been incorporated into design work as much as they could be (http://bryophytes.science.oregonstate.edu/page14.htm). Mosses as non-vascular plants, are unable to pierce the tissues of other plants and substrates and are not parasitic or aprophytic (Peck 2006). Only when higher plants take root in the moss mats will put the roof's structure be at risk. Moss B Ware products remove mosses from rocks and contribute to the accumulation of harmful pollutants in
urban environments.

Many cultures around the world have used mosses for hundreds of thousands of years for their numerous properties. Mosses are known for insulation for warmth used in bedding, boots, and house walls. In Northern Europe, stuffed sphagnum between the timbers of the walls was used to dampen the sound. Hypnum mosses were used for this kind of application and were thought to lead to extraordinary dreams (Kimmerer 2003, Glime 2007). In the Phillippines, mosses have been used as filler between wooden posts of walls and shingles of the roof. Mosses have also been used for their absorbent properties in sanitary napkins and diapers. For preserving salmon in the short term, they were wrapped with mosses to maintain moisture. Mosses possess anti-microbial properties and have been used for wrapping and protecting wounds, and they were used as insect repellant against mosquitos. Dating back to the French Stone Age, Tortula, Neckera crispa, and other mosses were used to make pottery less fat by improving the workability of clay and can be found in impressions in ceramic material as seen in Figure 2.0.7. Petecrete is a relatively new material mix of cement, peat moss, and perlite used for planters and outdoor furniture that attract mosses (finegardening.com/article/make-your-own-hypertufa-container).

Recently, mosses have encountered a resurgence in popularity. In 2011, Hisako Fujii published a book entitled Mosses, My Dear Friends, and sold 40,000 copies which popularized moss-viewing parties among women and moss-themed drinks and accessories. Gathering Moss, authored by Robin Wall Kimmerer, has drawn people to learning about mosses through her personal stories, scientific background, and illuminating the connections of moss with indigenous peoples. Companies in the United States, such as Planted Design, are designing moss walls precisely indoors to help create a link to nature and instill a sense of calmness (planteddesign.com/planteddesign/2016/3/10/). The beauty store, Glossier commissioned Lily Kwong to make a moss installation in a pop-up shop at a location in Seattle, Washington, drawing inspiration from the region's natural topography of Mount Rainier.

Propagation techniques are varied, and the original environmental conditions such as light, moisture, and substrate must match the elements of the new environment. Some methods include fragmentation and mixing beer, milk, yogurt, fish fertilizer, buttermilk, and compost to assist with the adhesion of the mosses. However, it is essential to note that additional substances will alter the microbiome of the moss, which could cause unexpected results. The American Horticultural Society recommends grinding mosses into powder and spreading it on the ground (Glime 2007). Adding sulfur, buttermilk, or aluminum sulfate helps to keep the pH below 5.5 for optimal moss growing conditions (Kimmerer 2003). Moss can also be grown between cheesecloth, where

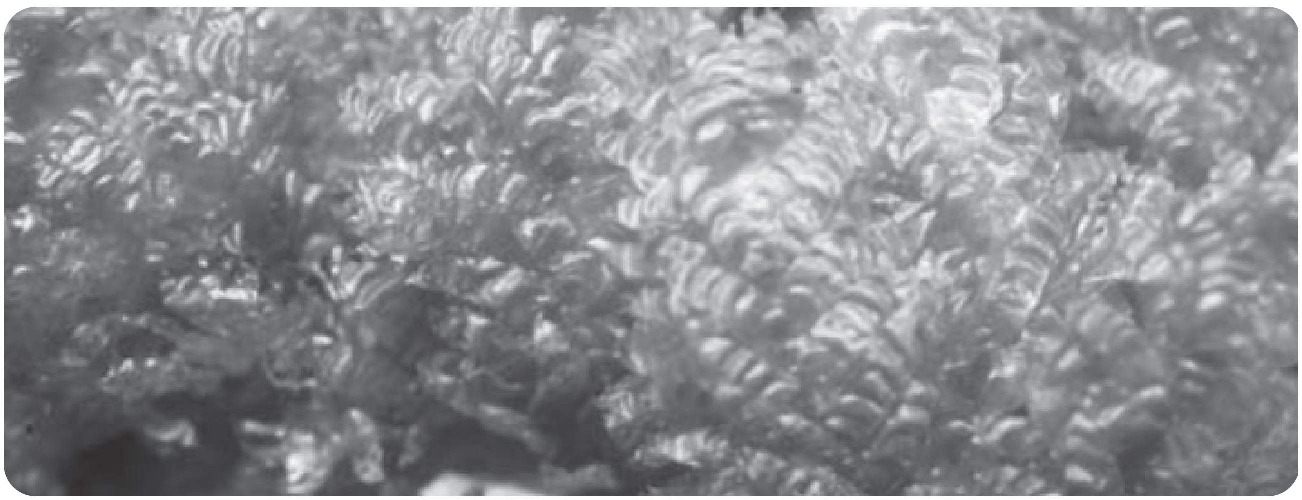


Fig. 2.0.7. *Neckera pennata* impression in pottery from French Stone Age.
Photo Courtesy of Janice Glime.

PIN/PATCH
During the transplanting process, mosses tend to pull away from the new soil substrate and shrink due to lack of moisture. To keep the moss patch moist to aid in attachment, turn the patch upside-down and wash the soil away. Pin mosses to soil with toothpicks or twigs.

FRAGMENT SPORE MIX
Mix a handful of moss, a can of beer, and a half teaspoon of sugar in a blender. Spread the mixture .5 cm thick on the ground. Expect moss gametes to show in five weeks.

OTHER INGREDIENTS TO CONSIDER:

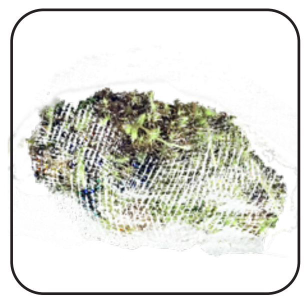
- Buttermilk
- Egg whites
- Rice water
- Carrot water
- Potato water
- Fish fertiler
- Water

(Ellis, 1992)

GRIND
The American Horticultural Society recommends grinding mosses into power to form and spread on bare soil. Maintain a pH below 5.5 by adding sulfur, buttermilk or aluminum sulfate.

RUB/CHECKERBOARD
In Japan, gardeners will dry moss, rub the moss between their hands to fragment it, and spread it on flats of soil similar to spreading grass seed. The plots are then cut into squares 20x20 cm, and stored in an elevated position until dry. The customer plants the squares in a checkerboard pattern. Over time, people step on the mats to break up the squares. The squares should be watered daily.

CLOTH LAYER
Lay a combination of partially dried fragments and spores between two layers of cheesecloth. Drape the cheesecloth over rocks. Over time, the cheesecloth will decay and the moss will adhere to the substrate.



LIGHT
Optimal light conditions for mosses are in a light shade. Shade provided by trees is suitable as long as litter does not bury the moss.

FERTILIZER
Mosses suffer under the application of fertilizer. They perform better when nutrients in the soil are lacking.

Fig. 2.0.8. A range of documented moss propagation methods.

spores can attach. With time, the cheesecloth erodes, and the moss takes over (Glime 2007). Janice Glime noted how she used nylon window screening to tie moss to rocks during the nine-week propagation period. Pinning the moss to substrate with toothpicks or metal pins will help secure patches of mosses as seen in Figure 2.0.8. In Japan, gardeners dry mosses, then fragment them between their hands and spread them on soil flats as one would produce grass seed. The moss plots are cut into 20x20cm squares and lifted to dry (Glime 2007). Planting them in a checkerboard pattern allows the moss to fill within the gaps of the square design. Misting for the first 60 days helps with the propagation, and it may take two growing seasons for the mosses to establish. It has been noted that it takes years for mosses cover the surface of a stone.

Designing living walls instead of green roofs could have twenty times the impact of increasing biodiversity and improving environmental conditions (Perez et al. 2014). Mosses are resilient to varying conditions which make them suitable plants for adapting to harsh conditions of vertical walls (Proctor 2009). The plant structure of mosses is slower to decay than other plants and serves as a protectant above their substrate materials. Mosses also hold the potential to provide benefits for historic buildings in protecting carved petroglyphs, preventing direct ultraviolet light on surfaces, and regulating moisture for fragile stone materials (Chiari & Cossio 2002). Moisture-attracting in nature, mosses have high evapotranspiration rates, which serve as possible cooling agents for reducing substrate temperatures, reducing heating costs, and on a grander scale reducing the urban heat island effect (Julinova and Beckovsky 2019). Furthermore, mosses are choice plants to consider for designs because they reproduce both sexually and asexually and therefore have high establishment and success rates (Rosentreter 2019).

Mosses provide a range of benefits in urban environments and enhance the human experience of place. The horizontal growth pattern of mosses broadly covers their substrate and provides a visual softener on impermeable architectural spaces. The textural quality of the mosses provides a sound buffer and creates green spaces, attractive qualities for humans (de Guevara 2018). The visual and environmental benefits hold the potential to impact psychological well-being (Besir and Cuce 2018). The overall visual benefits and improvements of space in urban environments also can increase property value (Chairunnisa and Susanto 2018). Applications of moss on architectural surfaces also prevent the risk of fire as records show that when moss mats experience lightning strikes, they may smolder but are unlikely to burn (Turetsky 2003). On newly burned soil and in burn fields, mosses are the first to colonize, such as the moss Funaria hygrometrica (McCune, Whitbeck mosslandscapes.weebly.com). In the application of disturbed areas, mosses are known to reduce soil erosion, such as in Christmas tree plantings and on herbicide ground (McCune and Whitbeck mosslandscapes.weebly.com). Additionally, moss propagation requires less maintenance and fertilizers or pesticides to control competitors in comparison to the use of other vascular plants that require additional nutrients and care (Chairunnisa and Susanto 2018).

Applications of moss in architecture and landscape architecture are relatively recent. A study on the effect of moss growth on mechanical performance on pre-vegetated concrete panels at the Universitas Indonesia explores three moss species, three surface textures, three substrates and finds this application successful (Chairunnisa and Susanto 2018). The BiotA lab at the University College London's Bartlett School of Architecture is reconsidering how architects define the skin of the building and are considering the exterior of buildings as a sort of bark on which to grow plant material in their production of bioreceptive concrete. (Sier 2017). BiotA has been using parametric design methods designing with channels in which the moss can grow in intentional ways. Green City Solutions based in Germany has been developing moss structures on flattened panels targeting air pollution hotspots in cities as seen in Figure 2.0.9. Their installations use remote technology to increase airflow, self-irrigate and remove pollutants, and test filters with scientific institutions (unenvironment.org/news-and-stories/story/air-pollution-eating-moss-cleans-hotspots-europe 2019). More research needs to be executed to identify optimal conditions for growing moss on varying substrates and about their ecosystem services as seen with potential in Figure 2.0.6.

Fig. 2.0.9. CityTree, designed by Green City Solutions, a landscape infrastructure moss bench with filtration properties and monitored with IoT. https://greencitysolutions.de/. Accessed 12/15/20.

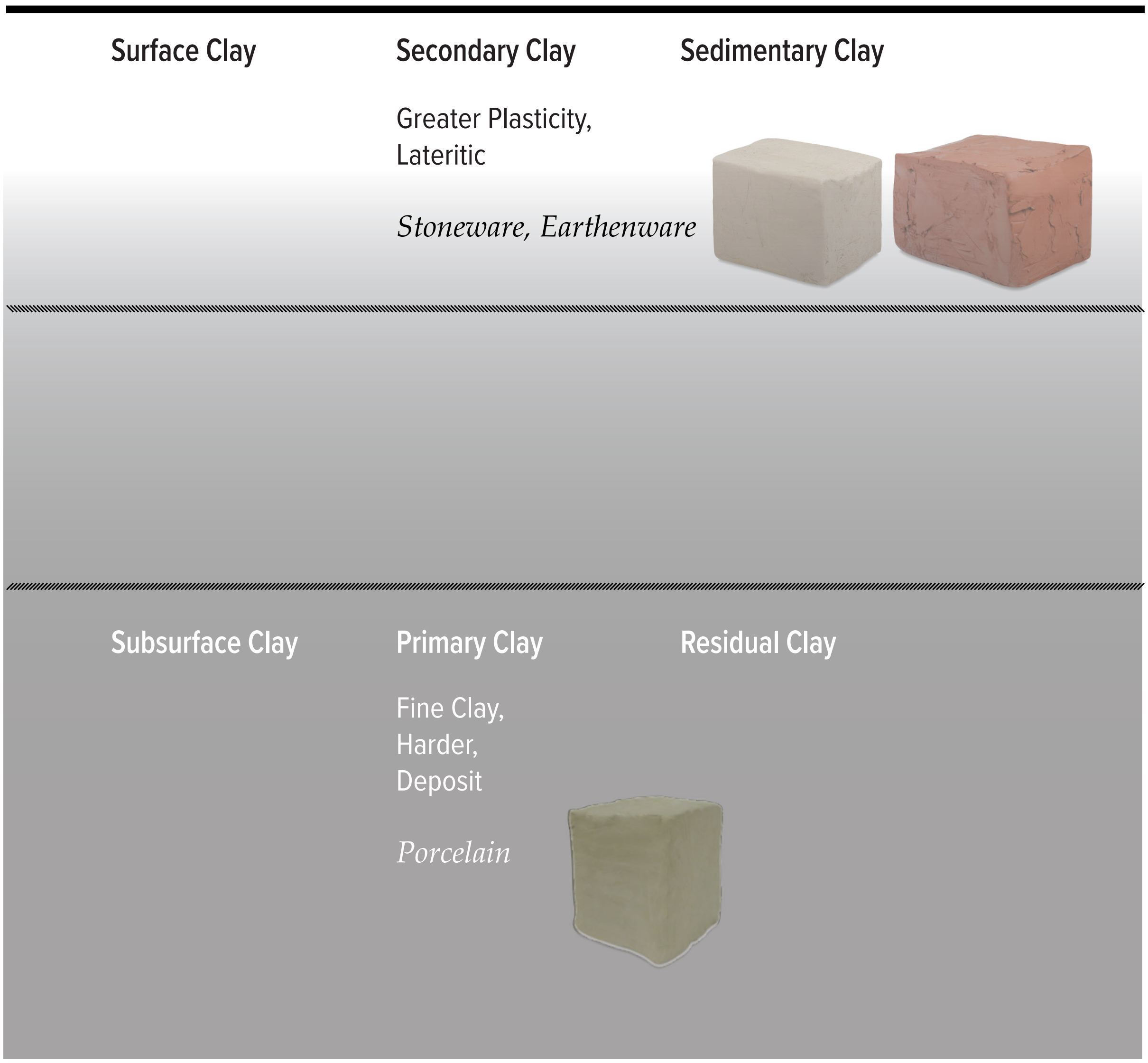


Fig. 2.1.0. Clay depths and terminology distinctions between primary clay and secondary clay.

2.1 CERAMICS

Clay, in a scientific sense, relates to argillaceous earth and is derived from the French word, argile. For tens of thousands of years, humans have been firing clay and transforming it into a stone-like state called a ceramic material. The etymology of ceramic comes from Keramos, meaning "potter's clay" or "art," and sheds light on the integral role that humans play in creating ceramic material (Searle 2013). Clays vary wildly in their composition based on their origin and are known for their physical and mineral properties. Most clays are primarily composed of alumina, silica, and water. Clays develop over geological time and result from the decomposition of igneous rocks, especially with the transformation of granite into feldspar. Primary clays are identified as residual clays originating from the source of extraction, such as kaolin, known as a fine, pure clay found in China. Sedimentary clay deposits identify secondary clays moved to a different location by water, wind, and ice and are typically found in layers as seen in Figure 2.1.0. (Cuevas and Pugliese 2020). Lateritic soils compose 74% of the earth's crust making clay a suitable and abundant material resource (Dethier 1981). Clay is an optimal material for design for its availability and other material attributes.

With the advancement of clay technology over time, "clay bodies" have been developed in response to project needs. Clay as a material is known for its hardness, density, durability, and many forms of appearance. The density and porosity of the ceramic materials are suitable measurements for identifying clay bodies. Density refers to the amount of water that a fired ceramic can absorb. Earthenware, stoneware, and porcelain clays hold a range of porosity and grain; towards the spectrum of finer clay bodies such as porcelain, density increases, and therefore porosity decreases. The size of the grain, additives, and amount of water in the clay body determines the porosity during the firing process. Generally, the properties of the clay determine the firing temperature to vitrify or harden the clay; earthenware fires to low fire (cone 015-1), stoneware to mid-fire (cone 4-6), and porcelain to high fire temperatures (cone 7-13). Most low-density clays, such as earthenware, are more porous and permeable, whereas porcelain becomes vitreous during the firing process and becomes resistant to infiltration and, therefore, freeze-thaw cycles.

Ceramics possess unique material properties that are suitable and unsuitable for a range of applications. Ceramics have high compressive strength and poor tensile strength (Bechtold 2015). Bending strength for a high-quality porcelain sink ranges between 7MPa and 30 MPa for typical tiles up to 120 MPa (Bechtold 2015) and shows increased strength when fired at higher temperatures. However, firing at higher temperatures to achieve greater strength is not always accurate in terra cotta. Brittleness and lack of tensile strength are properties that should be considered and compensated for depending on the application. High-stress areas should be avoided, including a significant change in wall thickness, sharp edges, openings, localized fasteners, sharp corners, and non-filleted intersections. The firing process that may result in vitrification allows for moisture resistance of the clay body and adaptability for freeze-thaw cycles in cooler climates. Non-vitrified clays are porous and can be advantageous for moisture absorption, such as evaporative cooling systems.

Most architectural ceramics are composed of earthenware and stoneware that contain sedimentary clay, also known as surface clay. Earthenware, which includes terra cotta, is a low-fire ceramic and has been used as roof tiles, thick tiles, bricks, and flowerpots. The structure needs to be load bearing for pavers and tiles, accommodate for traction, and sustain extreme weather conditions. Tiles are typically flat and bonded with mortar and sealed with grout to an underlying surface. Roofing tiles require finer-textured clays than those used in bricks and have a life span of 75 to 100 years or more (Bechtold 2015). Stoneware, composed of finer grain from a more rigid, shale-like sub-surface clay, is also used for architectural applications for façade elements. Porcelain is known for its low water absorption for the use of pipes and sanitation surfaces. Types of secondary clay include ball clay that informs the material plasticity; refractory clays determine the ability to retain structure during firing (Searle 2013).

Ceramic systems have been used for their acoustic properties as cladding systems to absorb sound on the interior and exterior of buildings. These ceramic materials are often composed of high porous clays such as earthenware and are formed into hollow objects. The hollow spaces may be filled with other materials to increase the

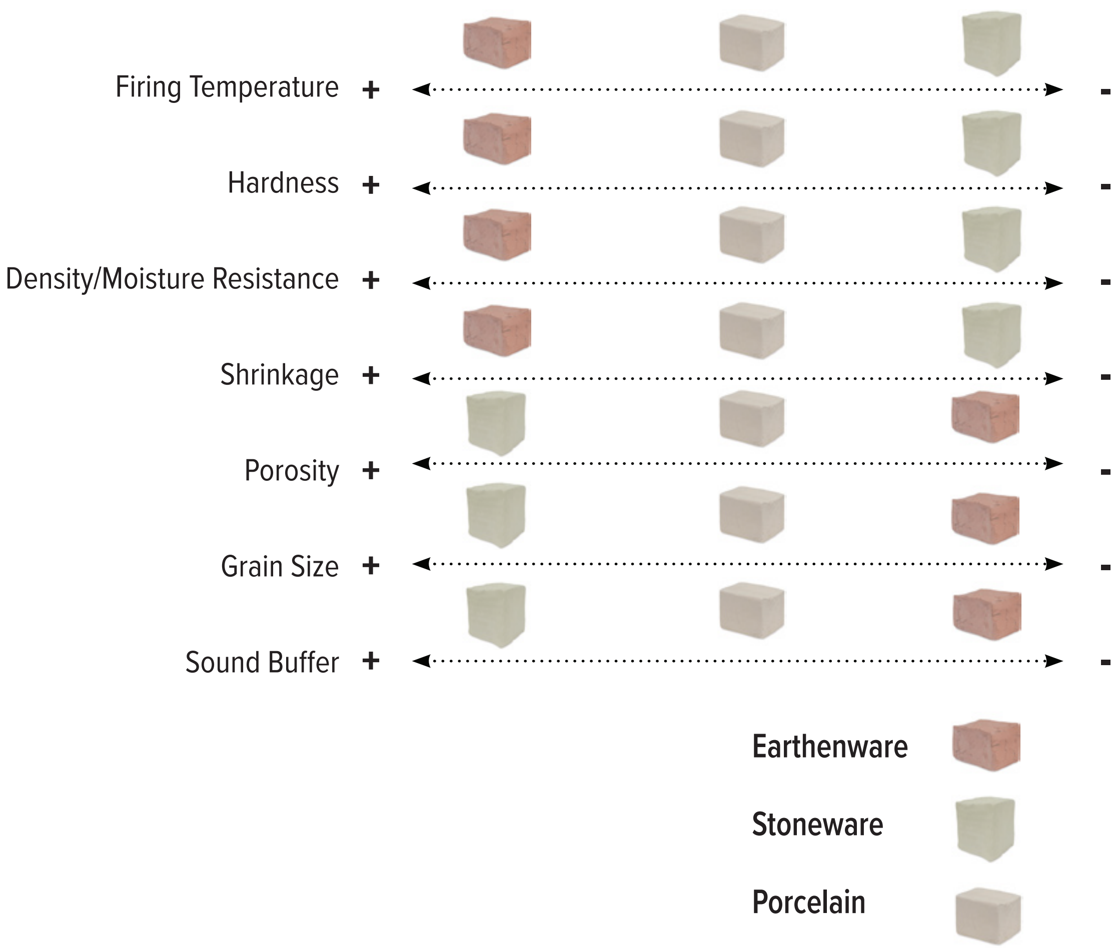
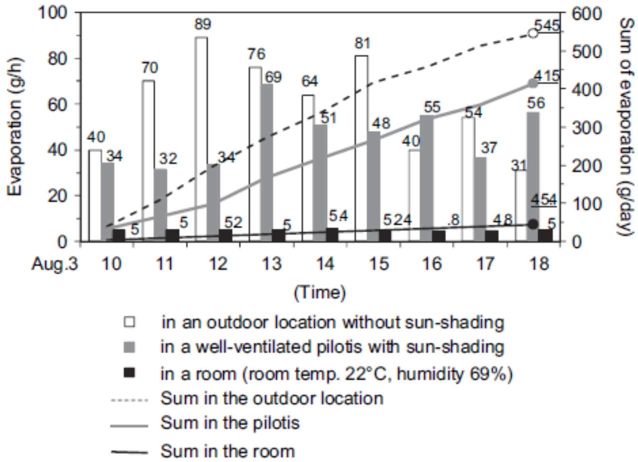
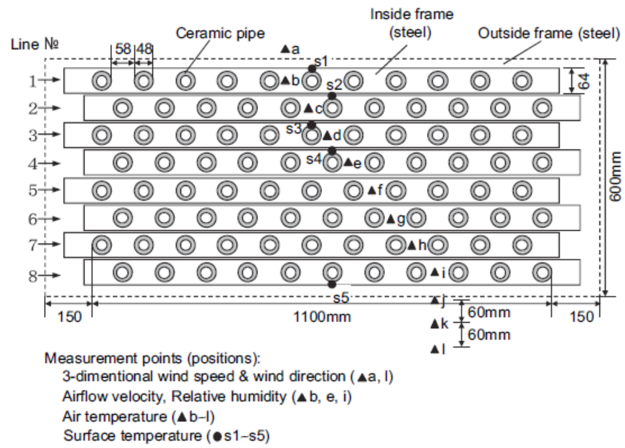


Fig. 2.1.1. Material attributes of clay bodies.



Experiment performed outdoors exhibited greatest rates of evaporation.



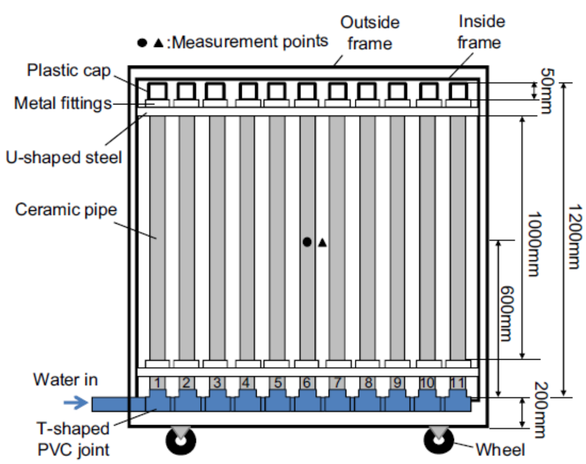
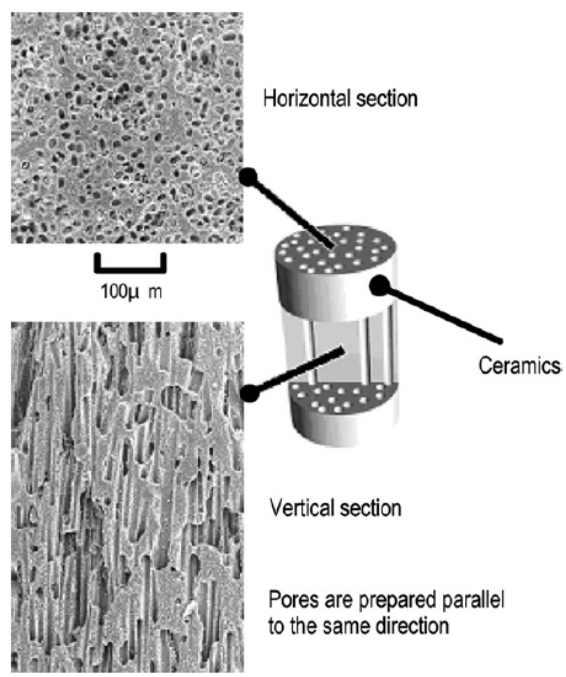


Fig. 5. Front view of the PECW mock-up and measurement locations.



Elongated, porous structure of ceramic.

Fig. 2.1.2. Experiment of porous tubular ceramic columns demonstrate evaporative cooling at ideal windspeeds. The experiment outdoors exhibited the greatest rates of evaporation.

sound absorbency and hung on an aluminum substructure. The sound that enters the open spaces bounces within the interior and generates heat. Some tiles have grooves on the back for direct mounting, and other systems are of a single-layer extrusion with slots and holes with the acoustic insulators placed behind the support.

Ceramics have been used in warmer climates for evaporative cooling. Evaporative cooling occurs in moisture when the heat hits the ceramic material, and water of the material evaporates, cooling ambient air temperatures. Other materials such as mosses have been paired with the evaporative cooling of mosses. An experiment considered how the greening of pavements could help counter the Urban Heat Island Effect (UHI) as seen in Figure 2.1.2. Varying materials such as water absorbing ceramic, non-water clay, mortar, and moss-covered clay were monitored for the surface temperatures of the tiles and the amount of water that evaporated from the sample tiles. The experiment showed that moss-covered and ceramic samples in the water absorbing state could suppress the temperature for radiation heat (Yasui 2018). The moss-covered sample remained cooler for a more extended period in comparison to the uncovered ceramic sample. In another research experiment, a series of ceramic tubes with long holes ranging in diameter from 5 to 50 micrometers were tested for the capacity to convey water one meter high (He 2011). Evaporative cooling was most successful at lower wind speeds from 1-3 meters per second and cooling efficiency at a maximum of 0.7 during sunny daytime periods (He 2011).

Workable clays contain about 25% water clay, so during the drying and firing processes, clay shrinks as it releases water at different states. This should be considered in the outcome of the design of the final work (Cuevas 2020). There are two stages to the drying and shrinking process. The first step is when the clay form first loses its water in the green state, the unfired state, and shrinks approximately 8-12% when the water moves to the center of the piece through capillary action as seen in Figure 2.1.3. Additional shrinkage occurs during the firing process when the chemical moisture is released from the clay body. More complex parts with deep concave and convex elements and flat tiles will likely shrink differently depending on the area exposed. Simple ceramic pieces will dry more evenly. Warping and sagging can occur during all parts of the drying or firing process, and accommodations can be made to aid in the work's success. Scaling up the work at the outset to fit the desired scale after shrinking is usually considered.

Different materials can be added to the clay for its material structure. Crushed ceramic, glass, or stone dust can be added to the clay body. The addition of nylon and paper fibers can add structure to the clay to help with the handling process before firing. Adding kyanite to the clay will reduce thermal stress and increase the strength of the final product (Bechtold 2015). Other organic materials such as sawdust and cereal can be integrated into the clay body to be burned out to increase porosity or create interesting visual effects. All clay bodies can be deflocculated to increase their viscousness for the slip casting process, for example. For surface effects, the application of slips, stains, and other slip resistant chemicals may be applied to change the surface. The color of clay bodies should not be confused with the material composition. Another example is that not all white clays are porcelain, especially with the common use of white stoneware. With additionally glazed surfaces, colors, and textures, the material ceramic substrate is easily covered.

After the ceramic material has been formed, glaze application serves a range of purposes to seal and protect the surface from wear, resist stains, and improve impact resistance. Glazes are glass-like and consist primarily of silica, alumina, and oxides. Silica comes from flint acting as a flux and causes to the glaze to melt, alumina from feldspar prevents glaze from running. Oxides allow for modifying the melting temperature further. Glazes must have a good fit to the clay body called the coefficient of expansion, or else the glaze will craze and chip off. Glazes have commonly been used to mimic the appearance of other materials. The first glazes date back to ancient Egypt and Mesopotamia for applying the stepped pyramid in Saqqara (2667-2648 BP) of the pharaoh Djoser. The glazes were used to emulate admired stones of lapis lazuli and turquoise (Bechtold 2015). Salt glazes have also been used and are drawn out of the clay body where it reacts with clay silica to form a glossy and colored surface. Environmental conditions such as temperature, humidity, and kiln type, and firing affect glaze outcomes.

There is a range of production methods that people have used over time to create clay and ceramic objects. The first objects were hand-built

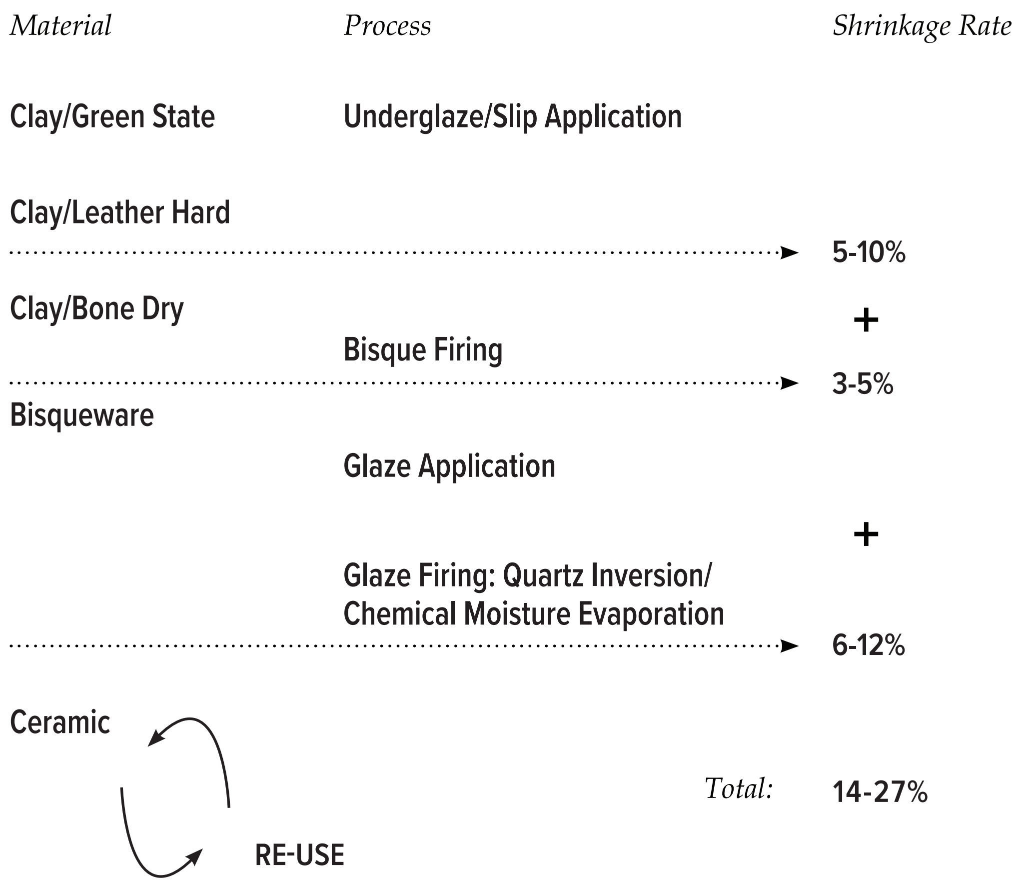


Fig. 2.1.3. Definitions, states of clay, and relating shrinkage rates through the making process.

Fig. 2.1.4. Reconstruction of Ishtar Gates at Berlin State Museum. Image and original data provided by Bildarchiv Preussischer Kulturbesitz; bpkgate.picturemaxx.com/webgate_cms. Accessed 5.6.2021.

using a coil-building method and are still utilized by ceramic artists today. Circa 3500 BC in the Middle East and China, the potter's wheel was the next technology to be employed, possibly one of the first technologies invented (Bechtold 2015). The rotation of the wheel with direct hand control allows for the customization of pottery to create axisymmetric shapes. Some of the earliest mold-making processes date to the Ishtar gates in Babylon circa 580 BP. The elements are brick-like and compose sixty lion reliefs in vertical layers. The production of this is likely mold-based, likely using one of the first pre-fabrication techniques.

During the ceramic-forming processes, processes are generally categorized between wet and bone dry (Bechtold 2015). When flat and slightly textured tiles are formed, they are generally formed between high-pressure steel molds, part of a single dry process working with clay from 3-7% moisture content. The extrusion is a wet process using clay with moisture content between 14-22% and creates linear parts through a cross-section system. Slump molding is also a wet process used to create curved elements. Die-cutting and plastic pressing can create unique shaped tiles and textures. Slip-casting involves creating a near-liquid clay to pour into a plaster mold for creating more complex geometries. Like wheel throwing, jiggering is also used to develop axisymmetric shapes using a profile guide. 3D printing with clay is a relatively recent ceramic production method.

The final process of clay production involves firing the work in kilns. Greater control of the firing environment has enabled the advancement of clay and glazes through measured experiments and firing at a greater range of specific temperatures. Kilns typically require air, fuel, and a heat source for the kiln to function. With gas kilns, cones measure the temperature, fall when at temperature, and determine the kiln's schedule. Clay firings were likely first executed in open-pit and have transitioned to kiln environments that offer greater control and efficiency, such as cross-draft kilns and high-volume computer-controlled tunnel kilns. Firings typically involve two types of firing; the first is the lower temperature bisque to remove moisture and the second is the higher temperature glaze firing. Historically, firings at the production sites have required fuel that ranges from wood to dung, coal and gas, and electricity. Small scale kilns generally range in size from 17-600 liters up to 6000 liters for gas kilns. Kilns are composed of fire brick which is a refractory material that prevents the kiln from melting.

Post-processing of ceramic work may involve grinding or cutting edges for the work to fit the context. Diamond wheels may be employed to grind into the harder material. It is sometimes optical for forms to be of square or chamfered edge to fit the placement correctly. Polishing, drilling, and cutting may also enable the creation of fasteners and work for installation needs. For most situations, the cutting is executed directly on the construction site.

The extraction of ceramic material has made an impression on the environment, and it is essential to consider the energy and lifecycle of working with clay. The building industry uses 40% of primary energy consumption in the United States and Europe, and using materials with less embodied energy such as clay could reduce this number. Life Cycle Analysis (LCA), is ideally a closed-loop system from cradle to gate and analyzes the energy, emissions, water consumption, and waste. Clay extraction occurs in open-pit mining and underground mining. Today's extraction methods are very efficient, where a miner can extract 800 tons of meter-size clay in a shift (Bechtold 2015). The distribution of clay involves packaging with cardboard and pallets, and fuel from trucking transport and clay production. The production of clay occurs locally and informs types of production to limit transportation labor and costs, typically 5-10% of the environmental impact of producing a tile. The process of drying the clay and firing kilns is the largest energy generation in the clay production process.

Working with clay offers many environmental and energy benefits. Firing methods have become more efficient in reducing firing energy. For example, at the Italian Ceramic Center in Bologna, Italy, energy needs for firing tile decreased from 10 GJ/t in 1970 to 5-6 GJ/t in 2010 (Bechtold 2015). Heat loss during firing accounts for the inefficiency of energy and can be enhanced in many areas worldwide. The advantage of clay is that it can be recycled back into the material preparation if not used. Crushed ceramic ware can be crushed up and used in the material process to decrease shrinkage. Other harmful chemicals that would otherwise go to waste can be mixed with clay material to be better stored.

The history of clay is rich throughout the world, and as Garth Clark noted in The Present Future of Ceramics lecture in 2016, “Ceramics is man’s oldest technology”(Clark 2016). Ceramics are regarded as the first human-designed material instead of materials extracted directly from nature and reshaped, such as branches and stone (Bechtold 2015). From around the world, traces of the earliest documented ceramic work give us clues to the first clay works. A general theory is that clay was used to line woven baskets to assist in water transport. When the clay dried, it shrunk in form, creating a new, disparate object. Pottery shards are documented in Gambols Cave, Kenya, with impressions of woven patterns (Wright 1992). Early documentation of ceramic work shows the integration of plant material and goes back to 14,000 BP in China and Japan. In China, dating to the Yanshao Culture of the Stone Age from 5000 – 3000 BP, coil pots with red and black clays were integrated with plants and grasses (Hargens 2016). During the French stone age, there is documentation that people mixed mosses such as Neckera, Crispa, and Tortula into the body of the clay to augment its workability. Prints of the species of mosses are found within the fired clay body (Flora of North America 2013). Research shows that when Neolithic hunters and gatherers settled, the creation of ceramic material became more widespread. Ceramics have been used in a wide range of applications for practical use that include storage, drinking cups, and bowls for fermenting fish and exterior use in paving, roof, and the composition of walls (Carr 2020). The practical aspect of pottery over time shows its wide range of modular and independent interior and exterior environments. Non-functional work is made for more a metaphorical or aesthetic appreciation such as garniture or as a sculpture. Even though functional work in clay may have been the first to be produced, there is evidence that metaphor and symbology have been expressed in clay such as in the Venus of Dolni Vestonice, which dates to 29,000-25,000 BP of the Stone Age. This work was excavated in 1920 in Moravia, Czechoslovakia (https://www.britannica.com/topic/Venus-of-Willendorf). Remaining on the surface are fingerprints of a child that handled the piece during its unfired state. Constructed kilns on the site give information to the first identified ceramic production (Bechtold 2015).

Historical applications show how clay has been used in architectural applications as seen in Figure

2.1.4. For example, in the Near East, sun-dried clay had been used as a plaster and brick material. In early architectural applications, terra cotta friezes and cladded columns decorated Wooden Greek temples. Animal or water power has was used early on in Greek times for mixing clay to assist with the serial production of roof, wall, and floor tiles. The ability to create permeable tiles enabled the transfer of these materials to other locations in Northern Europe's wet climates. The Romans also embedded hollow clay vessels into their concrete domes to save material and lighten the dead load. This technology was somewhat lost after the fall of the Roman Empire. Islamic architecture produced compelling mosaics between 750 and 1300 CE within their doubly curved domes (Bechtold 2015). Beginning in the 1850s, with the rise in popularity of iron and steel structures, terra cotta cladding was used to protect the buildings from fire. Hand-pressed molds accommodated for shrinkage and applications and were part of the development of high-rise buildings in the 19th Century.

Recently, architects such as Frank Lloyd Wright and Jorn Utzon in the Sydney Opera House have led to a revival of the application of ceramic material in the 20th Century as seen in Figure 2.1.5. Eladio Deiste used ceramics structurally in waving walls and shells in Uruguay and Spain. When ceramics were used in freestanding applications such as rain screens and other barrier applications from the elements. Thomas Herzog developed the first ventilated ceramic system in Munich in 1984 (Bechtold 2015). Renzo Piano continued to apply ventilated architecture systems in France. The collaboration of manufactures with architects usually engages several manufacturers with architects as their core business model. Manufacturing companies in the ceramics industry today are composed of small craft-based firms and highly-industrialized companies.

Within the past decades, the practical surface treatment of buildings is being reframed as performative architectural ceramics in the context of material systems (Bechtold 2015). Multifunctionality and new aesthetics are at the core of redesigning buildings, landscapes, and cities made possible through new technologies, fabrication methods, and workflows. Mass-production equipment and digitally monitored machines allow for specialization for specific projects. Fastening substructures range from being handmade, which are typically low-volume and flexible and or industrially mass-produced with high volume and inflexible outputs. New forms of technology allow for finding a middle ground with creating specialized parts with more excellent production rates. The performative nature for specific applications can respond to the flow of moisture, heat, sound, and light, adding to the benefit of the interactions of the urban environment.

Architectural ceramic manufacturers, landscape furniture companies, and artists investigate the applications of ceramic material outdoors. The Boston Valley Terra Cotta company for example focuses on development and research for sustainable terracotta applications through the recent launch of TerraTrust. Areas of research focus include glaze colors, resistance to UV light, compressive strength, and manufacturing techniques. They recently produced glazed terracotta tiles using the RAM press to create a spectacular green façade for the John and Mable Ringling Museum of Art – Center for Asian Art in New York City, for example. Boston Valley Terra Cotta is host to the Architectural Ceramic Assemblies Workshop (ACAW), in its fifth year engaging with architecture professionals to discuss designing with ceramic work. Jeff

Fig. 2.1.5. Sydney Opera House by Jorn Utzon.

Fig. 2.1.6. Claudia Issa, Visiting Artist at Kornegay Design. Photo credit: Kornegay Design. https://kornegaydesign.com/craft/visiting-artists/claudia-issa/. Site accessed 5.6.21.

Schmuki, a ceramic artist and digital designer, explores the intersection of growing plants on clays and has created hydroponic gardens intended to outlive the exhibition, agritecture, and portable gardens (https://www.jeffschmuki.com/gardens). Kornegay Design, a landscape forms company, collaborates with visiting artists to prototype original designs explored by working ceramicists like Claudia Issa and Ian McDonald (http://kornegaydesign.com/) as seen in Figure 2.1.6. Their explorations in clay translated to landscape applications are an exciting way to push ideas into formal work.

In moist climates like the Pacific Northwest, mosses grow abundantly on various synthetic and natural materials, commonly on the fringe, out-of-reach, and unmaintained places. Mosses are low growing and often found growing in novel ecosystems of the cracks and grooves of the urban fabric where water collects. It is interesting to consider which spaces are underused, small, and visible, and easily retrofitted in the built environment that could be enhanced with ceramic substrate and moss propagation. Mosses can hold up to some traction, but it would be ideal for designing less-trafficked spaces to encourage growth. Interstitial spaces such as fences, near the base of buildings, and along the edge of stairs work for places where mosses could be placed for propagation. For areas with minimal pedestrian traffic and high traffic, reducing pollution and increasing green space include medians, retaining walls, and billboards. Due to the small size and lightweight material of the hybrid combination of clay and moss, existing infrastructure with slight retrofitting such as building facades, roofs, public transportation infrastructure, and bollards could additionally take the application of mosses. Many unexpected and novel places in the built environment could intersect and host hybrid ceramic and moss applications.

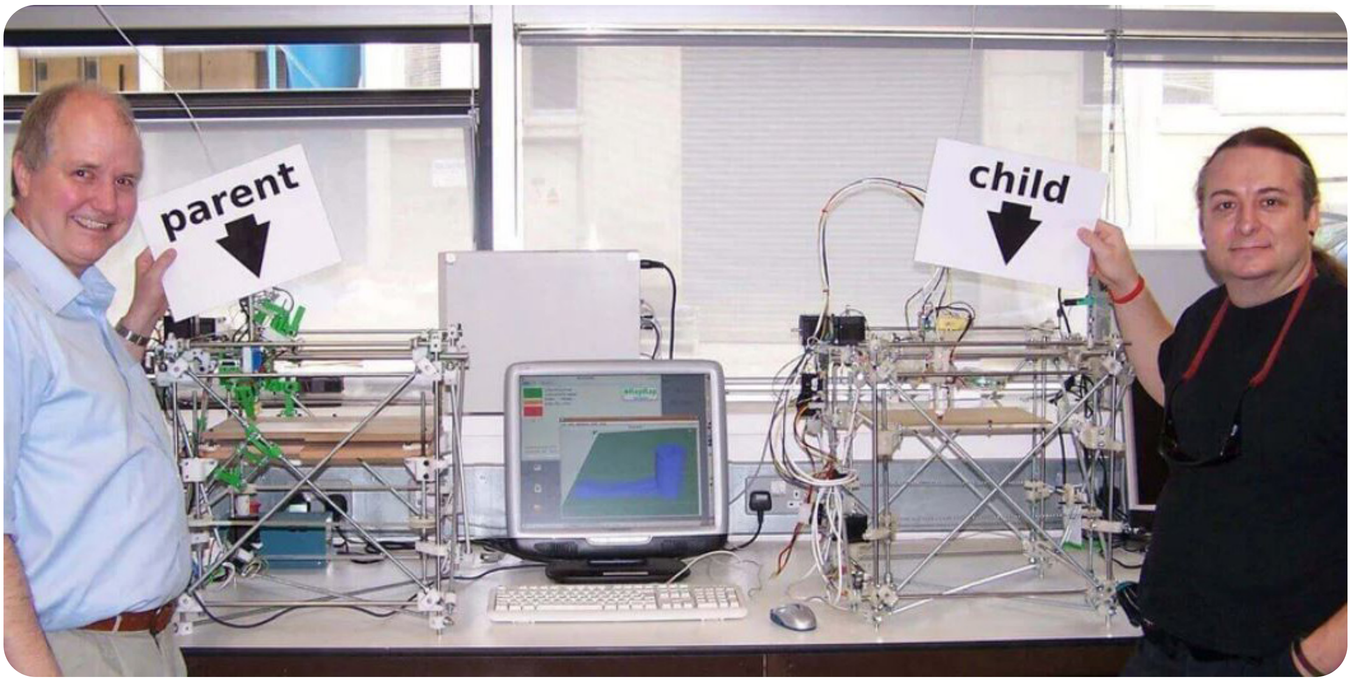


Fig. 2.2.0. RepRap Printer with parent and child and produced by Adrian Bowyer (left) and Vik Olliver (right) of the RepRap Project. All parts of the child printer were printed from the parent. Photo Credit: All3DP https://all3dp.com/history-of-the-reprap-project/. Site accessed 5.6.21.

2.2 3D PRINTING

The history of 3D printing is relatively recent and began with introducing additive manufacturing (AM) in the 1980s to the traditional methods of subtractive fabrication in industrial manufacturing. The 3D printing process relates to the deposition of ink-jet printers where the material is added and joined in layers to create a form from 3D modeled data. There are many types of 3D printers and there are currently five distinct types of 3D printing: extrusion, direct energy deposition, solidification of powder, photopolymerization, and sheet lamination (Berndsen 2010, Getter 2009, Clark 2010). A range of materials can be processed for 3D printing, ranging from plastics to sand and food to ceramics. The advancement of computer software through computer-aided design (CAD), manufacturing (CAM), and photogrammetry have significantly shifted the processes of design, prototyping, and manufacturing.

The progress of 3D printing has been driven forward by private and public entities investigating new approaches to 3D printing and decisions on providing 3D printing as open-source or closed-source technology. Hideo Kodama of Nagoya Municipal Industrial Research Institute in 1981 was the first to publish the working photopolymer rapid prototyping system. In 1984, Charles Hull invented stereolithography (STL), which involves hardening the deposition of liquid polymers under ultra-violet light (Savini 2015). Laminated Object Manufacturing (LOM), a process that consists of cutting objects from paper using a laser and applying a plastic coat to the top and bottom side to meld them together. At the University of Texas, a Selective Laser Sintering (SLS) printer created forms using a laser to melt particles of powder and was patented in 1989 and produced by DTM in 1992. During the late 1980s, the Fused Deposition Modeling (FDM) technology was formulated based on the deposition of thermoplastic material layer-by-layer using a 3-axis robot and was later patented by Stratasys in 1991 (Savini 2015). New technologies such as Electron Beam Melting and Laser Engineering Net Shapes are also under further development.

Into the early 2000s, printers were expensive and unaffordable for most individuals. In 2005, at the University of Bath, Dr. Adrian Bowyer worked on a Rep Rap (Replicating Rapid Prototyping) project where a printer produced most of its parts as seen in Figure 2.2.0. This Rep Rap printer was composed of a 3-axis robot mounting one or more extruders using Fused Filament Fabrication derived from Fused Deposition Modeling. The hardware and software for this printer were open-source and used Arduino. This open-access component to the project is crucial because it enabled users to participate and modify their printers. Also, in 2006, at Cornell University, Fab@Home was another printer developed for open-source hardware and software. This 3-axis system allowed for printing with multiple extruders and a range of materials. Websites such as Makerbot's, Thingiverse, and Shapeways make free file sharing accessible.

In 2006, MakerBot Industries was established in New York City and distributed DIY kits. MakerBot has since moved from open-sourced to closed-source hardware and is currently owned by Stratasys Inc. The initiative to make 3D printers open-source sparked a sort of revolution in 3D printing. N. Gershenfeld, in the 2000s at the Media Lab at the Massachusetts Institute of Technology, taught a class on "How to make (almost) anything." This movement has been a springboard in fabrication laboratories at a range of universities, individuals printing at home, and at Maker Faires for sharing more information. Today, about 30,000 patents for 3D printed forms have been published, and one can buy home 3D printers from over 100 companies (van Wijk, 25).

3D printing applications are essentially limitless, and the materials for 3D printing have greatly diversified. Used in fields from aerospace to biomedical engineering, most 3D printing for the industry has involved the printing of polymers and metals. Ceramics and glass have generally received less attention by industry due to the inherent difficulties of fusing these materials in the kiln. Materials used for 3D printing explore photopolymers, wax, aluminum, thermoplastics, and paper. Additionally, harder substances such as titanium, nickel, ceramics, epoxy resins have been used. Exciting materials such as clay have been used for construction, chocolate, and reusing waste plastic material. A fast-growing area for 3D printing includes prosthesis and tissue engineering for bones, blood vessels, and teeth.

Different 3D printers share a range of similar features that determine the outcome of the print. Printers generally are mechanical robots run by small stepper motors and deposit layers moving along three axes. The nozzle diameter of the extruder and the size of the build plate range significantly. For 3D printing, the main parameters of interest are melting temperatures, melting viscosity, and coagulation time. For design work to be 3D printed, models begin by being formed digitally with CAD, CAM, and photogrammetry programs. After the model has been created, it must be sliced into a gcode for the printer to read. Slicing software is available for free and with purchase online. Most 3D printers are manufactured in the United States, followed by Japan, China, Israel, and European countries. With the advancement of the printers and higher production rates, costs for printers have generally decreased.

Producers and designers are two main drivers that impact the innovation of 3D printers. Producers generally advance hardware and software applications, and larger entities are typically slower to innovate to the demand of the designer. Smaller producers can pivot and innovate more competitively. Designers using 3D printers can push the technology forward by inquiring about new design approaches. 3D printers are still limited in their technology, such as requiring plug-in power, requiring in-person management, and connecting directly to the internet for efficiency in downloading data from an online database. The 3D printing industry can reach wider audiences by turning towards more open-source online-based networks to increase access and education around 3D printing. With the advent of shared technology and digital communication, there is increased potential to co-create across regions and disciplines.

The process of 3D printing is preferable for the production of certain kinds of products for a variety of reasons. In the research and development of products, it is helpful to create prototypes rapidly with affordable, local materials and in smaller quantities. The 3D printed prototype helps visualize the final work before it moves into the final material and cost of the product. 3D printed final products are helpful for where the large market volume is uncertain, so only needed for printing smaller quantities. If various forms, colors, and sizes are required, 3D printing for customization is a streamlined way to produce diverse objects quickly from data. Finally, 3D printing offers a means for local production, reducing the energy and time involved in long-distance transportation. Aerospace, biomedical, and consumer product industries sectors are most likely projected to utilize 3D printing technology for advancement and growth soon (Marscommons. marscommons.marsdd.com/3dprinting/ tech-trends-new-applications/).

The 3D printer gives its user agency and opens the possibilities for a new revolution in manufacturing, already called the third industrial revolution (van Wijk 2015). The 18th-century revolution was made possible because of the ability to produce goods on a mass scale, changing the structure of the economy and society. Having access to 3D printers in factories, in laboratories, and at home gives users the ability to print ad hoc, removing the need to purchase items mass-produced. When objects are needed, need repair, or replication, 3D printing desired objects, where 3D printers are more accessible, becomes possible, changing the economy. Furthermore, with the recent focus on plastic production in the economy and negative climate impacts, it is now possible to print with biomaterials that can be recycled and part of a sustainable, circular economy where end-products are not unusable waste. Ton Runneboom, an expert on manufacturing, believes that shifts in manufacturing will occur and 3D printing will become a dominant manufacturing technology because it is cheaper in the end (van Wijk 2015).

Using different materials, recent innovations in 3D printing have enabled designers to produce work on grander scales, such as buildings. Enrico Dini Developed a 3D printing technique through the sintering of sand to create structures. Various combinations of material allow for printing certain elements and filling them with other materials. For example, Behrokh Khoshnevis has worked on a contour crafting technique of printing with a carbon fiber cement mixture (www. contourcrafting.org). DUS Architects have created a house for a canal using the "Karnermaker", a large-scale home printer as seen in Figure 2.2.1. The rooms were printed as modules, and the exterior is printed in one swoop to bind the house together. Printing different parts of features with other materials is an effective way to optimize material production. Neri Oxman, a designer who prints with a range of materials, believes 3D printing houses will happen as advancements in printing and weaving technologies develop.

Several printers are designed for 3D printing with clay. The 3D PotterBot series is based

Fig. 2.2.1. Karnekar 3D Clay Printed House by DUS Architects in Amsterdam, The Netherlands. https://www.dezeen.com/2016/08/30/dus-architects-3d-printed-micro-home-amsterdam-cabin-bathtub/ Site accessed 5.6.21. Photo Credit: Sophia van den Hoek.

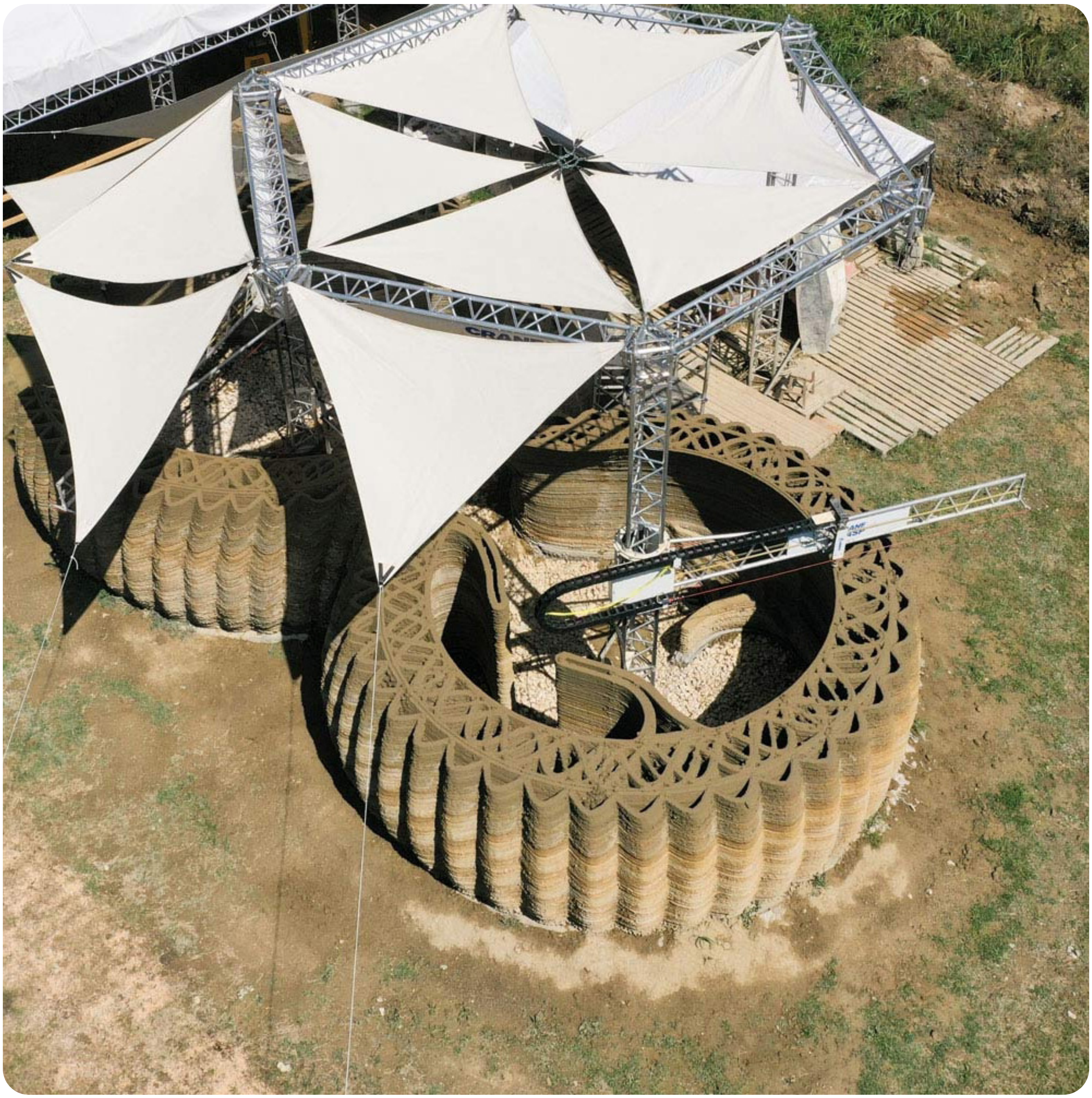


Fig. 2.2.2. TECLA printer by WASP for 3D printing inhabitable buildings constructed of clay. Photo Courtesy of 3dwasp.com/en/3d-printed-house-tecla/. Site accessed 5.20.21.

in the US and manufactures clay 3D printers that use the material extrusion method and can output large volumes of undiluted ceramic materials with its heavy ram extruder using a continuous flow system. The precision is due to the reduction of the hose and the precise control of flow. Recent printers such as the Scara V4 print up to one meter high. WASP is a 3D printer manufacturer based in Italy and is also known for its clay printer's ability to print tall works, including houses and shelters as seen in Figure 2.2.2. The material extrusion system comes in a kit and pre-set-up printer to help users of all abilities start to print. Another recent printer is called Stoneflower, based in Germany and can print with a range of malleable materials. Cerambot, based in China, advertises its printers as the most affordable on the market. There are air compressor and stepper motor printers to order parts to assemble and that arrive pre-assembled.

Clay is an exciting material to 3D print with as it is an extension from art, craft, and architecture applications and, with new technology, can take clay design forward. 3D printing with clay is not unlike the traditional way of making pots through the coil-building process. This type of new digital fabrication gives form to a new machine aesthetic. When clay is deposited through the extrusion method, it compresses the layer below it and builds on the previous layers. Printing in the clay gives the designer a specific control of the form and outcome, sometimes produced through the precision of parametric design that is otherwise difficult to achieve through hand-built and wheel-thrown work. 3D printing is a form of production accessible to people with a range of experience and accessibility needs. The digital design and output of printing in clay invite people to work across disciplines and new ways. Choosing to work with clay as a medium is an environmentally friendly resource for its abundant nature and lack of need to mix with other possibly harmful additives. It is possible to mix clay with other additives for structural or aesthetic attention. Works produced in clay can later be recycled and used for other applications limiting waste commonly produced in other materials such as plastic.

Innovations in 3D printing make it possible to print on larger scales and create diverse extruder movements informing the possibilities for new designs. However, there are still some limitations in the clay printing process that are inherent to the design of extrusion deposition printers and in the response of clay as the material. Clays possess anisotropic properties as they are composed of elongated platelets. 3D printed clay is stronger along the grain of movement of the nozzle as platelets align with the extrusion and slight compression of the clay (Cuevas 2020). The extrusion method of 3D printers is visible in most 3D printed work forming a discrete horizontal layered aesthetic as seen in Figure 2.2.3. Miniature stepper motors run many printers, so the mechanical properties compared with other manufacturing methods hold less power for working with more significant amounts of material (Cuevas 2020). Due to the force of gravity and clay's soft consistency during 3D printing, overhangs and protruding forms need consideration for support if there is a risk for collapse. Also, due to the slight compaction of the clay during the print as opposed to the compressed technique of manually working with the clay, 3D printed work is generally weaker and more porous than wheel-thrown or hand-built clay work. Printing work that exceeds the thickness of an inch increases the risk of exploding during firing if the clay is still wet. Printing flat, paneled work also creates issues as the drying time will be uneven from the outside edge to the interior f the work resulting in warping, curling, or cracking (Cuevas 2020). These limitations provide foresight for designing more strategically in clay 3D printing and developing more advanced 3D printers accommodating clay's properties.

Fig. 2.2.3. An example of extrusion by 3D printer that emulates coil building process. Clay was mixed with sawdust to increase porosity.

2.3 DIGITAL DESIGN

With new possible typologies and applications in the landscape, using 3D digital modeling software such as Rhino and CAD provide pathways for reaching a designed product. In Rhino, for example, it is possible to manually construct forms, piece by piece, through a visual approach like the additive process of drawing. Plug-ins such as Grasshopper hold the potential to push design work forward by approaching design through algorithms that identify specific parameters to achieve different results. This approach includes selecting input options such as node-based (symbolic or text) diagrams representing design choices to deliver a range of visual outputs (Tedeschi 2014). Working parametrically with Grasshopper expands the options for design iteration, visualization, and analysis processes. With proficiency in Grasshopper, it is possible to achieve a range of outcomes relatively quickly by adjusting the inputs. The construction of an algorithm is the design of a process and the output of the object (Tedeschi 2014). Parametric design can help support rapid prototyping and iteration common in research-through-design approaches.

In the context of landscape architecture, digital design was adopted slower due to three ideas: that creativity was purely human, there is an unmediated connection between the brain and hand, and that technology distances the designer from the real world (Walliss 2016). In the early 2000s, Marc Treib's writing in Drawing/Thinking: Confronting an Electronic Age (2008) expressed the potential loss of agency working digitally and led to a slowness in adapting digital technology. These ideas come from a more limited understanding of technology because these technologies have been developed to emulate hand-drawn techniques. Karen M'Closkey of Peg Landscape Architecture argues that new media can create beyond hand-drawn techniques and utilize unique capabilities. While hand-drawing is still valuable, there is excellent generative power and analytical abilities in employing digital design.

Digital technology in itself does not drive innovation. The designer uses intent and agency through technology to achieve a certain income. Technology and advancements in design work concurrently as designers express their needs to push the possibilities of technology tools. Digital design presents a new language and logic of design

(Walliss 2016). During the landscape architecture design process, the field was understood in relation to Postmodernism and demonstrated alignment with cross-disciplinary nature in cultural studies and geography, and the arts. This association in theoretical alignment divorced the profession from adapting digital innovations such as in the fields of architecture, engineering, and construction.

Grasshopper was developed in 2007 by David Rutten at Robert McNeel and Associates (Tedeschi 2014). The program is free as a download and is tied directly with Rhino. The node-based plug-in runs from left to right and includes a range of parameters, components, and other tools such as panels to show information. Once a script is built, and the desired form is created, the work can be "baked" into Rhino to preserve the geometry and explore other geometries generated from the script. Grasshopper holds many capabilities in that it intersects with different programs, expands on original work design in Rhino, and accommodates many plug-ins. With Grasshopper, it is possible to generate a design for movement within the software using Kangaroo, run sedimentation flow simulation models, and provide inputs for responsive technology like Arduino. Through the Grasshopper plug-in, Galapagos, for example, it is possible to take one surface and generate new populations rooted from the original to test fitness based on specific parameters that include number of points, depth, and height to create optimal surfaces for solar radiation.

Parametric design in Grasshopper makes the development and translation of ideas into forms such as 3D clay printing possible. Albin Karlsson and Johanna Jonsson collaborated to generate a structure entitled "The Weave" using parametric design into an architectural-sized ceramic 3D printed structure in Sweden. Pairing the metaphysical with design, they looked to philosophy and Hindu temples' design for exploring design concepts. Their analysis found certain geometries that they aimed to incorporate into the design of their 3D prints, such as projection, staggering, and repetition (Karlsson and Jonsson 2019). In addition, they incorporated their elements throughout the design process inherent in the tool, such as mirroring. Through the process of analysis, digital design, and self-fabrication using different materials, they built the structure with their hands at the human scale with the overall goal of creating more enchantment between humans and the material world in the West (Karlsson and Jonsson 2019).

Conversations around digital design and 3D printing question the human relationship in work. For example, Jonathon Keep, a clay 3D printing researcher, investigates meaning in work that is not produced directly through the impression of his hands but through code and working on the screen. In clay, he sees deep relationships between art, nature, and the material of clay and poetry between the vessel and the human condition as seen in Figure 2.3.6. Considering three types of scale (handheld, lap, and floor) and realizing the work in physical form in clay, he feels the work relates to the human body and grounds the work (keep-art.co.uk).

Fig. 2.3.0. Jonathan Keep's work exploring paths of emerging movement in curves through proportions, ratios and relationships between elements from the most microscopic to the massive such as planetary paths. http://www.keep-art.co.uk/digitial_curves.html Site accessed 1.12.21.

Fig. 2.4.0. Olympia Sculpture Park in Seattle, Washington designed by Weiss Manfredi.

2.4 BIO-DESIGN

Exploring moss growth on media such as clay and ceramic stands on the shoulders of various fields relating to architecture and manufacturing to ceramics and sustainability practices. This section on background research touches on fascinating historical and contemporary accounts which support the cross-disciplinary exploration for designing with and foregrounding mosses. This research extracts connections and ideas to remind us of our current moment in the design, reflect on historical methods, and offer inspiration to drive design between living and non-living materials forward in the context of the built environment.

Landform Architecture

Landform architecture is a recent approach in architecture that merges with interconnected living, synthetic, and geological considerations in landscape architecture. There has been a recent intersection of architecture and landscape architecture in Landscape Urbanism for designing with flexible programming, extended continuity, and marginal spaces. For the last twenty years, architecture has been influenced by a movement towards becoming more fluid, transformative, and responsive to change (Allen 2011). With new developments in technology, it is easier to design and manipulate surfaces for buildings that might change and evolve; however, the construction materials are essentially still the same. Additionally, there is criticism where even if structures are designed for evolution, the changes are minimal, and the building largely remains static. When comparing facilities with ecology, change occurs faster within ecology than a building and faster within the building than the geology that lies below it (Allen 2011).

As James Corner has said, that "sowing the seeds of future possibility, staging the ground for both uncertainty and promise." The preparation of surfaces for future appropriation differs from a merely formal interest in single surface construction." (Allen 2011). Within this statement, Corner sees a vision for the possibilities inherent in hyperfunctional surfaces that pair plants as the living with non-living geology materials. Approaches in landform architecture are typically less formal and emphasize dynamic systems and processes over formal logic (Allen 2011). The Olympic Sculpture Park in Seattle, Washington designed by Weiss Manfredi is a fitting example of landform architecture that explores the hard infrastructure of the building and nearby roadway infrastructure with the softscape of the natural elements at varying elevations as seen in Figure 2.4.0. There is much potential in pushing forward the synthesis of structural materials and plant life to create extending and emergent design adjustments that improve the ecological mosaic of the built environment.

Earth-Sheltered Design

Earth-sheltered design is another architectural form relating to landform architecture and earth architecture and blends into the landscape more harmoniously than a conventional structure fully above ground. Bermed and underground structures are the main types of earth-sheltered design, with bermed buildings being more common than underground buildings surrounded by earth (https://sustainability.williams.edu/green-building-basics/earth-sheltered-design). Concrete, waterproofing, and wood are all materials used to compose earth-sheltered buildings (https://www.energy.gov/energysaver/types-homes/efficient-earth-sheltered-homes). Bermed buildings are typically designed with passive solar features such as south-facing windows to maximize solar potential and reduce added energy costs. (http://www.2030palette.org/earth-sheltering/). A building underground runs closely with the average temperature of the earth of 55-60 degrees Fahrenheit, requiring less cooling in summer and heating in winter. Other benefits include reduced noise, less alteration of the landscape, and resiliency with exposure to environmental events. Earth-sheltered buildings are more suitable for drier climates than humid areas where moisture collection and flooding may interfere with the structure of the building.

Earth Architecture

Unbaked earth and additive materials have been used to construct buildings for thousands of years, dating back to Mesopotamia and Egypt and in different regions worldwide (Niroumand 2013). During the middle ages, construction in unbaked materials was used in Europe and in North America. The Spanish conquerors in the Americas influenced techniques used in earth architecture (Sameh 2014). In Europe, following World War I and II, and during the 1970's energy crisis,

Fig. 2.4.1. Rammed Earth Experimental House in Paslek, Poland. Photo Credit: Teresa Kelm.

European countries have turned to rebuilding with earth architecture as an economical and sustainable material as seen in Figure 2.4.1 (Dethier 1970). Recently, earth architecture and earth-sheltered design have been used primarily by environmentally conscious clients and designers but are growing in interest as more people are looking for more environmentally friendly architectural alternatives (Rael 2009).

Some of the first buildings were characterized as "facal" and were built using simple tools, creating a safe place near caves and cliffs. Another type of early architecture is called the "pit house," composed of lumps of mud and was established when hunter-gatherers became stationary and developed more permanent housing. Various methods have been used to construct earth materials, including turtle construction formed by pressing clay into a basket. Formed adobe bricks and Terrone bricks were also used to construct the building by layering and tiling the bricks. There are additional records that buildings up to ten stories high in the Middle East and Africa were constructed with great integrity. In recent history in the United States, adobe bricks were used by the rich or very poor and were deemed undesirable due to this socioeconomic contrast (Niroumand 2013). Today, over one billion people still form homes from mud, typically living in rural areas, using locally sourced mud. Thus, there is a rich history of designing with mud in architecture, and this information can continue to inform sustainable and affordable architecture in the built environment.

Today, we face the impacts of a climate crisis and need to actively reduce factors that contribute to environmental degradation by reducing extraction, pollution, and energy needs. Recent architectural approaches involve high construction costs, demanding in energy consumption, and require significant transportation. According to the World Business Council for Sustainable Development (WBCSD), 40% of the world's energy is consumed by the building sector (The EEB Report 2009). Designers and building construction can look to more historical methods paired with innovative technology and sustainability, such as designing with earth as material. In places where earth architecture has been historically built, such as in Egypt, there is significant potential to reintroduce earth architecture by combining old and new technology to reduce cost and environmental degradation. Using local earth as architecture is advantageous because it is a flexible material, is suitable for recycling, and can adjust to the size of households by phased expansions over time (Sameh 2014). Recently built earth architecture applications demonstrate the success of the material for the community. An example of rammed earth architecture includes the Chapel of Reconciliation built in 2000 in Berlin, Germany by Reitermann and Sassenroth and has shown to attract the public as a landmark (Rael 2009). In colder weather climates like Sweden, Norwegian architect Sverre Fehn used traditional earth materials for The Eco House, demonstrating the potential for earth construction with simple treatments to sustain in a range of climate conditions. Additionally, German-Austrian architecture duo Anna Heringer and Eike Roswag, used design to build upon traditional cob building techniques for The Handmade School in Bangladesh. The community built this building as an educational and empowering driver and received recognition through the Aga Khan award.

There are a variety of construction methods used in earth architecture that offer a range of benefits. Approaches to building with earth architecture include mud brick, rammed earth, infill, and bag construction. Carbon emissions are more reduced during construction and in the performance of the building. For example, earth architecture requires 1% of the energy for production compared to fired brick or concrete (Minke 2000). The material is low in contaminants, fireproof, reduces condensation and fungal growth. Earth architecture can be easily recycled back into the earth. Working with clay is a malleable, low-cost, accessible material that can be readily available for construction, especially following disasters (Khalili 1983). Because earth buildings are composed primarily of clay, they are suitable for having plants grow on facades and roofs, providing temperature regulation inside and outside of buildings, and clay is effective at storing heat through its thermal mass. Earth material is also the best at guarding against electromagnetic radiation against other construction materials, as is the study's outcome at The University of Kassel's Building research Institute (Little 2001).

Despite the many benefits that earth architecture offers, there is a range of user, social, and political perceptions that have slowed the acceptance

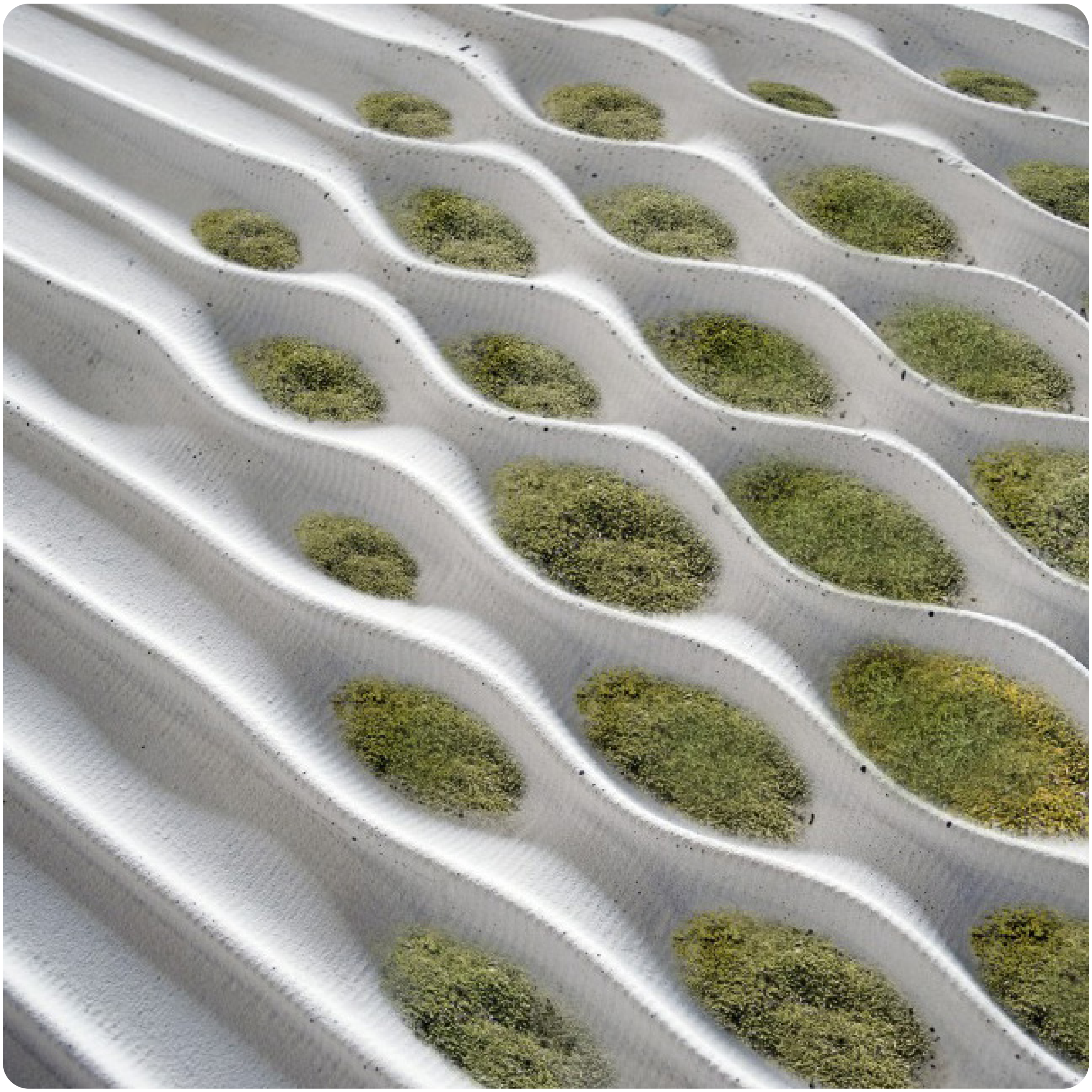


Fig. 2.4.2. Photo credit: BiotA Lab, one cemenititious panel of three. http://www.richard-beckett.com/portfolio/items/bioreceptive-facade-panels-epsrc-funded-research-computational-seeding-of-bioreceptive-materials/ Site accessed: 3.16.21.

of earth architecture. Firstly, a common perception is that earth architecture will erode quickly. However, with skill, proper material compositions, and maintenance, the earth architecture will endure exposure to different conditions across time, such as the Great Wall of China. Aesthetics are another concern in that clay in the construction context is unable to be reshaped in attractive approaches. Because of clay's abundance and affordability, the material is sometimes associated with lower social classes. Commercial monopolists working in developing countries neglect clay as an option and choose to supply conventional materials, inhibiting the potential to work with clay. Standardizing clay as a building material is also complex, with the varying compositions of clay worldwide (Sameh 2014). Policy and government can play a significant role in advocating for clay materials as an environmentally viable material for the building sector.

Biophilia

Emerging architectural applications investigate the possibilities of new materials and the capacity for growing plants on these surfaces. The building envelope such as roofs and living walls have been targeted for greening applications. These green typologies are borne out of the need to increase biodiversity in urban environments by increasing permeable surfaces and offsetting carbon emissions. However, much of the existing greening applications require significant irrigation, regular maintenance, and high implementation costs. Even though cities have been working to address the urban heat island effect by incorporating greening applications, there has been a decrease in cryptogamic cover surfaces (algae, mosses, lichens, etc.). The disappearance of these plants has primarily gone unnoticed likely due to their small scale.

Buildings, roofs, fences, and walls are exposed to a range of hydrophilic conditions, and exciting design potential exists with new moves in bio-integrated architecture. A biologically bioreceptive concrete has been developed by "Computational Seeding of Bioreceptive Materials," an interdisciplinary research team at the University of College, London, and has since been taken forward by Penine Stone Limited and Transport for London (TfL) as seen in Figure 2.4.2. They have developed a cementitious material studied for pH values, porosity, and water retention properties to promote the establishment of cryptogamic plants. Important design components include forms that collect and direct water and material that increases water absorption for promoting plant growth. The team also recognizes the need for "diverse and bioreceptive substrata – what Marcos Cruz calls "architectural barks". For example, incorporating protrusions and recesses helps plants adhere when they are susceptible to impact in the desiccated state or during high winds. This sort of surface complexity includes considering three kinds of scales that range from micro (material), meso (surface), and macro (tectonic) scales (Cruz and Beckett, 2016).

With biointegrated systems, the material and form should be designed for specific environmental contexts. Environmental conditions vary according to region, so there is the need for further design development for a range of climates. The project developed by the London team has piloted materials for three different location tests. The first installation comprises 20 GRC Limestone concrete at East Putney Station in London and will be up for the next three years. The 32 GRC Limestone concrete panels are installed at St. Anne's Catholic Primary School. This installation was co-designed with biologists Anete Salmane and Rushi Mehta to investigate moss growth on various substrates. Material tests that examine buffered sound are being carried out on these surfaces. Thirdly, an 8 GRC limestone concrete wall is in a private garden in Edinburgh with a highly porous concrete with lower types of cement than existing concretes. The vision for this work is to find a meaningful intersection of architectural materials that are entirely able to hold photosynthetic processes throughout and not just at the superficial level.

Biophilia, a concept from psychology and philosophy, is rooted in building and nature as the primary architectural design input. Biophilia means an attraction towards nature. Eric Fromm, a social psychologist in 1964, first used the term "biophilia" to explain the appeal to things that are alive and vital (Kayihan 2018). Biophilic design recognizes the gap between the built environment and the natural world and looks to queues in the natural world for the design in the built environment. People who live and work in buildings where biophilic design is incorporated generally have a more effortless time healing,

Fig. 2.4.3. Steno Copenhagen Diabetes Center connects patients to Nature. Photo Courtesy of Vilhelm Lauritzen Architects, Mikkelson Architects, and STED Landscape. https://www.archdaily.com/803283 Site Accessed: 5.6.2021.

focusing, and feeling positive (Alusaed et al., 2006). Fallingwater House designed by Frank Llyod Wright falls into the category of biophilic design with placement near water; however, the ecology of the house remains separate from its environmental context. Steno Diabetes Center in Copenhagen, designed by COWI A/S, Vilhelm Lauritzen Architects, Mikkelsen Architects intentionally creates an integration with nature, weaving the outdoor environment with the indoor environment to support healing as seen in Figure 2.4.3. (Archdaily 2017).

In the 1990s, the adaptation of biophilic design became adapted into the built environment with concern for restorative and ecological design prompted by increasing environmental concerns. The movement towards green and sustainable design can be seen in the literal form of the building in organic forms. Seven criteria have been established by Kellert and are articulated and include seventy principles (Kellert and Cabrese 2018). These criteria include direct experience of nature, the indirect experience of nature, and the experience of space and place. Browning et al. addresses a different category, including criteria such as nature being in the area, nature analogs such as organic form, and the nature of the space, including elements such as prospect and refuge (Kayihan, 4).

Biomimicry

Another closely linked approach to biophilia is biomimicry. Biomimicry involves looking to nature to find solutions to address ecological efficiencies in the built environment. Nature has worked most efficiently over time to form patterns in the biotic and abiotic aspects of the environment. As designers, we can look to nature for inspiration at different scales and relationships and consider organisms, behaviors, and ecosystems. Approaches to biomimicry can be broken down further in form, material, construction, process, and function (Mansour 2012). As cities look to establish climate action plans and incorporate more buildings with net positive environmental impacts, they can adapt regenerative design and biomimicry approaches. Transferring the knowledge of ecology and biology in the built environment of architecture and landscape architecture holds exciting potential for designing cities with healthy urban ecosystems.

In 1982, Otto Schmitt coined the term biomimetic and was reintroduced by Janine Benyus in 1997, co-founder of the Biomimicry Institute (Benyus 1997). Biomimicry has sometimes been misconstrued as buildings mimicking natural objects globally but is better understood as the transfer of natural principles of technical questions and could be integrated into enhanced technologies (Ramzy 2015). Biomimetic approaches relate more to design technology and involve a three-step process that includes research, abstraction, and implementation (Pohl 2015). Problem-based approaches and solution-based approaches are two main approaches to biomimicry design. With problem-based approaches, the designer identifies the design problem and looks for solutions in organisms or processes the natural world for a human problem known as “Design to Biology” or “Challenge to Biology”. The solution-based approach is “Biology to Design,” when a biological principle is first identified by biologists, for example. The designer adopts this concept into the approach before the goal is defined. Relating design approaches to biomimicry can be truly inspiring and eye-opening to the designer, more closely connecting them to the natural world and similarly for the users who actively use the designed space.

Green Roofs

In landscape architecture, green roof implementation and research have increased over the last ten years. A driver for the increased implementation of green roofs is to offset the adverse effects of urbanization through green stormwater infrastructure. Green roofs have been implemented in many regions worldwide and offer a range of benefits (Shafique 2019). These benefits include stormwater management, reduced urban heat island, increased urban plants, wildlife habitat, roof life, enhanced air quality and water quality, decrease energy consumption, reduced noise pollution, and increased recreation and aesthetic value. However, there is controversy over the efficiency and high cost of green roofs. Green roofs are composed of layers or filters, drainage, insulation, root barrier, waterproofing membranes, and growing medium to support plant life (Department of Planning and Local Government, 2010).

Green roofs are classified by substrate depth and fall into four main categories: intensive, semi-intensive, single-course extensive, and multi-course extensive roofs. Intensive green roofs are

Fig. 2.4.4. Hanging Gardens of Babylon, Painting by Ferdinand Knab in 1886.
https://allthatsinteresting.com/hanging-gardens-of-babylon. Site accessed 5.6.21.

the deepest greater than 12 inches and hold the most weight in plants and water. Single-course is extensive roofs with a substrate thickness of 3-4 inches, have mostly sedums and require no irrigation. Of the four types, single and multi-course extensive roofs are most common worldwide (Shafique 2019).

Historically, some of the first green roofs were noted to exist as part of the Hanging Gardens of Babylon constructed around 500 BCE as seen in Figure 2.4.4. Many Scandinavian countries have also covered their roofs to protect against extreme conditions (Shafique 2019). Green roofs were reincorporated during the 1960s in Germany during the energy crisis with more significant expansion in the 1980s. Today in Germany, more than 10% of buildings use green roofs for environmental benefits. The research generated by different languages in different countries has been a limitation in sharing research. Recent standards on green roofs have been illustrated in the Standards and Testing Materials (ASTM) in 2006 and more recently in the 2009 USEPA report (Shafique 2019). These standards have led to the enforcement of new policies with environmental objectives. For example, for areas with new buildings in Portland, Oregon, 70% of that area requires green roof cover.

Roof areas account for 40-50% of the impervious surface cover of cities in general, so considering the design of green roofs, there is potential for improving the surface cover of roof surfaces. A meaningful amount of research has been invested in plants' performance, such as certain sedums that can survive in extreme weather conditions. Green roof enhancements include adapting a green-blue roof that manages water and the relationship with plants. Hybrid applications of photovoltaics can improve the energy efficiency of urban environments and increase shading for plants below. Green roofs are also known for food production and serving the needs of the community. There are multifunctional applications in the technology, program, and plants used in green roofs to improve their performance and reverse the adverse effects of urbanization.

Bio-Integrated Architecture

In addition to green roofs and living walls, products on the market at different scales investigate the benefits of bio-integrated surfaces.

For example, green City Solutions' has designed CityTree, a bench attached to a four-meter-high moss hedge known as the world's first intelligent biological air filter and installed in several cities across Europe (https://urbannext.net/citytree/). Founders Peter Sanger and Liang Wu invented the CityTree for densely populated cities with little extra space and high pollution. Mosses are very effective at absorbing particulates. The benefits of this multifunctional bench reduce particulate matter and absorb nutrients in a 164-foot radius, and function similarly to 275 trees for 1% of the space (thegoodstartup.com). Absorbed particulate matter ranges from 0.1 microns wide to ten microns – the smaller, the most dangerous (https://www.wired.co.uk/article/citytree-air-pollution-uk-piccadilly). According to the American Lung Association, particulate matter is the most hazardous pollutant to human health, and this issue is critical to address in urban environments. The bench is also composed of a built-in irrigation system powered by solar energy, rainwater collection, and IoT measures the structure's performance. The façade of the moss interface also holds the potential to serve as advertising in a billboard or creative outlet as public art.

ECOncrete is another company founded in 2012 by Dr. Shimrit Perkol-Finkel and Dr. Ido Sella, marine ecologists. They co-founded ECOncrete in response to the world's populations living near coastlines, exacerbated climate conditions, and sea-level rise. The products are designed with bio enhancing concrete additives, and recycled materials help with structural integrity while adding to ecology. The composition of the products reduces Greenhouse Gas Emissions up to 45% compared to a Portland-based mix (https://econcretetech.com/econcrete-sustainability/).

Tide Pool Armor, ECO Armor Block, and Eco Mats are a few of their products that retain hardscape features such as riprap while creating a definition for local ecosystems providing a substrate for plant life and increased carbon sequestration over time. The Tide Pool Armor emulates rock pools allowing plant and animal life to occupy the concave blocks, Armor Blocks stand up to extreme hydrological forces, and Mats provide bank stabilization as seen in Figure 2.4.5. The Tide Pool Armor product received the Global Biomimicry Design Award for outstanding ecological and structural performance. The products of ECOncrete comply with ASTM and EN standards required for coastal construction.

Fig. 2.4.5. ECOncrete, Tide Pool Armor, https://econcretetech.com/. Accessed 12/15/20.

Terraplanter produces ceramic hydroponic planters for indoor use that invite plants to grow on the exterior of the container. Kickstarter first supported this work in spring 2020. The planter functions by filling the interior, allowing minute amounts of water to excrete to the grooved and patterned surface, supporting root growth as seen in Figure 2.4.6. The planter consists of a base for collecting excess water, the main body, and the lid for preventing evaporation. Research for the product included exploration around the structure, material, and plant needs. Determining the right balance of a hydroponic and porous material was key to the material development. The products are composed of low-fire terracotta and are therefore all-natural and reusable. The planter was designed to hold seeds and water and enable a hold for the roots to investigate plant applications. Parametric design was used to figure out the planter's formal elements. Various plants have been shown to grow on the surface of the terraplanter, and mosses are a type of vegetation that can be applied to the vessel's exterior. This product serves as an example of how mosses can grow on ceramic substrate if they receive a sufficient amount of moisture to metabolize.

Through intentional shaping, clay is a medium that expresses design, and 3D printing as an innovative tool can be understood as an extension of the hand in making that cannot be formed through other technologies. Digital design software and processes are translations of ideas and will continue to be explored. With further advancements in digital design and clay 3D printing, there is exciting potential for making these design approaches more accessible towards generating design work that aims to enhance the ecology of the built environment. Beyond the field of landscape architecture, investigating the hybridized relationship between 3D printed substrates and mosses holds excellent potential for improving the underestimated spaces of the built environment.

Fig. 2.4.6. Terraplanter options, by Terraplanter. https://www.kickstarter.com/projects/terraplanter/terra-planter-the-inside-out-hydroponic-planter-pot Accessed 5/18/21.

Moss Survey

Observe

Proto-Experiment

Microscope

Assessment

preliminary

Research

Mosses

Ceramic

Digital Design

3D Printing

Bio-Design

Architecture

Landscape

Product Design

Experiment

Case Studies

Survey

Highlight

Tech Set-Up

Firmware/ Slicer

Grasshopper

Plug-ins

Gcode

Rapid Prototyping

Applied Research

Design Development

Case Studies

Analog

Digital

3D Print

Modify

Typology

Barnacle Test Interfaces

Kiln Fire

Speculative Design

Design Development

Design Framework

Benefit Analysis

time

3. METHODOLOGY

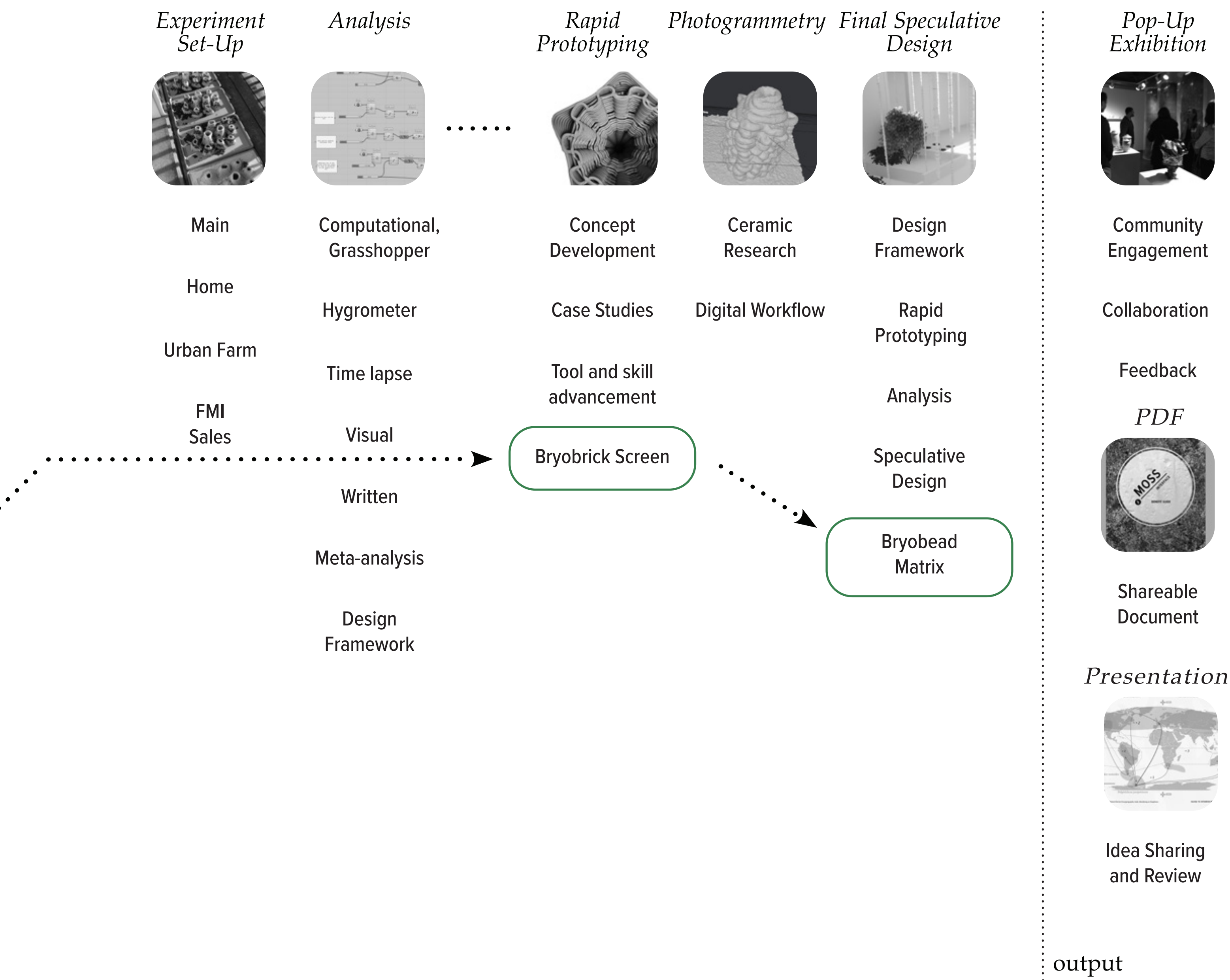


Fig. 3.0.0. Methodological process through Master's Project highlighting outputs of design process.

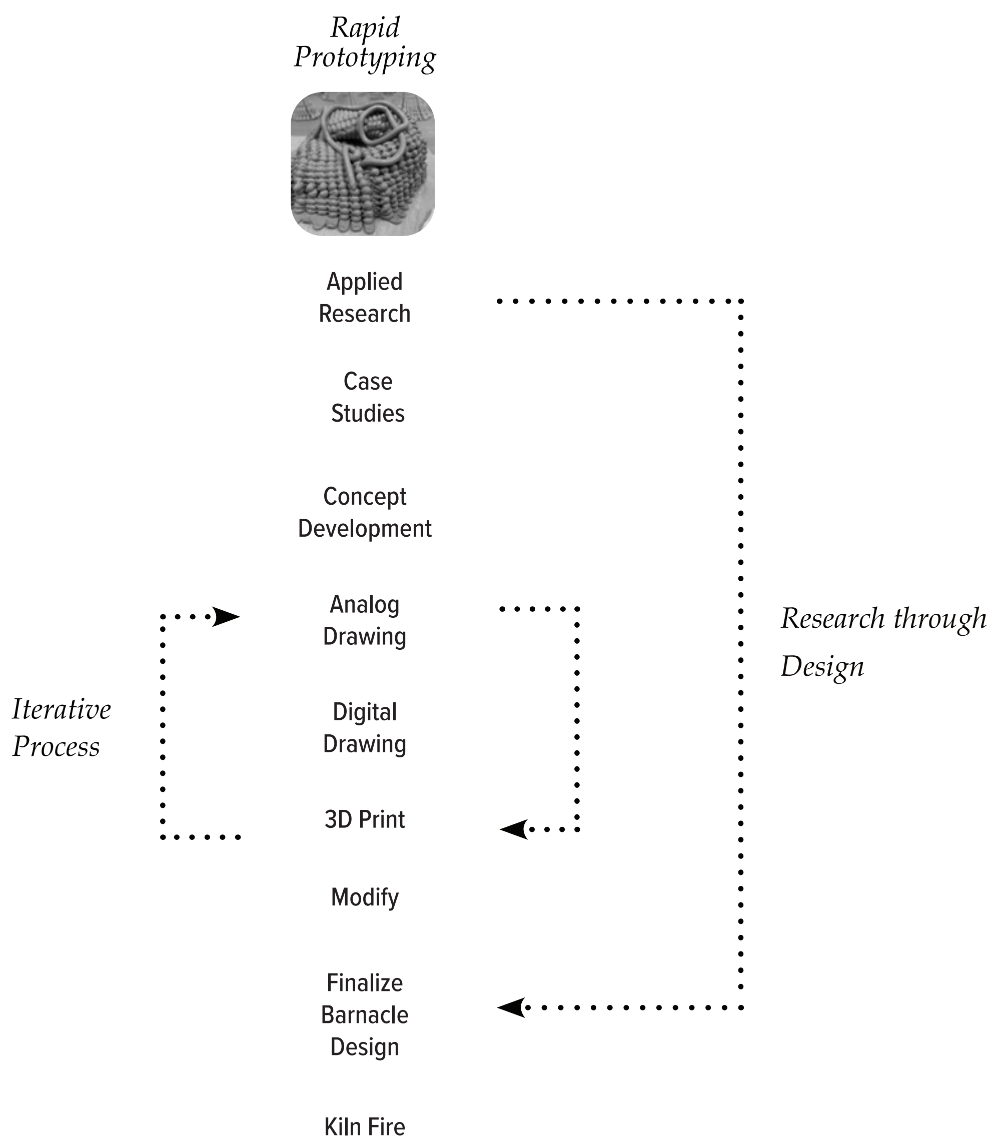


Fig. 3.0.1. Rapid prototyping process and the intersection with Research-through-Design.

Several methodologies have been incorporated in the production of this Master's Project as seen in Figure 3.0.0. An effective way to explore optimal patterns designed in clay and observe and analyze mosses' growth is through Research through Design. Research-through-design allows landscape architects to engage more directly with landscape processes through the design activity as a research method. This relatively new theory of landscape architecture can help generate knowledge through spatial design. The aim to reach practical objectives through research can be understood where research is the activity that explains the physical and aesthetic outcomes of design. Generating new knowledge through the experience of design informed by background research can lead to new ways of understanding and expanding landscape architecture. By systemically using theory to develop and test ideas, new insight is developed, leading to new theories and more possibilities for applied design. Research-through-design is often conducted in cooperation under different disciplines. This Master's Project comprises different phases that fall under different theoretical frameworks developed by Deming and Swaffield, Lenzholzer, and Nijhuis and Bobbink.

Insight comes from paying close attention to what is happening and learning about objects' responses in real-time in the landscape, such as an experiment. The word experiment is derived from experience, and cultivated knowledge comes from conducting experiments with different parameters. Landscapes are composed of many layers of interconnected elements across time. These variables within the landscape can be analyzed as a sort of laboratory. An example of this in landscape architecture is Piet Oudolf exploring the interactions of plants in juxtaposition to learn about successful and surprising outcomes such as winter interest. Different information can be gleaned for different purposes for what is useful. For example, historically, at HJ Andrews in 1948, old-growth forests were studied for their ability to mill wood as efficiently as possible and for building new roads. Today, as the climate crisis negatively affects the health of our environment and human experience, there is a need to explore ideas to generate understanding for designing performative and resilient landscapes.

The experimental process leaves a mark in the world and should be thoroughly considered for the benefit of people and the environment.

The act of the experiment holds the potential to change the landscape. Landscape architects ought to ask how the profession interrogates values and ideas by using research-through-design to change the landscapes in which we live. Through the lens of science, information is often distilled to reach towards facts and theories. In the context of landscape architecture, our practice connects many ideas from different fields for understanding outcomes to augment the profession. During the Master's Project, this experiment generates outcomes and information about the experiment that inspire new forms through rapid prototyping and speculative design. This inquiry seeks to find results at the end of the experiment and find interesting findings that lead to more questions.

Landscape design deals with form and meaning and is concerned with the organization of a physical, functional, and aesthetic arrangement of various structural elements to achieve desired social, cultural, and ecological outcomes (Nijhuis 2012). Landscape architectural research can be understood as being morphological and situated within two- and three-dimensional elements of the natural, cultural, urban, and architectonic elements related to ecological, social, and economic contexts. Content and form of the landscape are related. The analysis and understanding of data and concepts can be synthesized and expressed in either two or three dimensions (Nijhuis 2012). The experiment part of this work was an experimental design study that involves understanding the composition of elements and isolating them in specific contexts (Nijhuis 2012). This type of study generates knowledge by understanding the effects of varying the design solutions in a particular context. Then, the experimental variables can be tracked over time to create knowledge and applied to the final design study. The investigation is done on the composition element and scheme, and the experimental transformation is the type or principle. The choice of the isolated composition elements is transparent, and this spatial knowledge informs the next activity. The formal characteristics of the object are linked to the investigation or situation using generalized knowledge, which can be implemented in the design study (Steenbergen et al. 2008). What is left out of the Master's Project from the analysis of Nijhuis is the original plan analysis to comparative analysis as seen in Figure 3.0.2.

Within the theoretical framework matrix of Elen

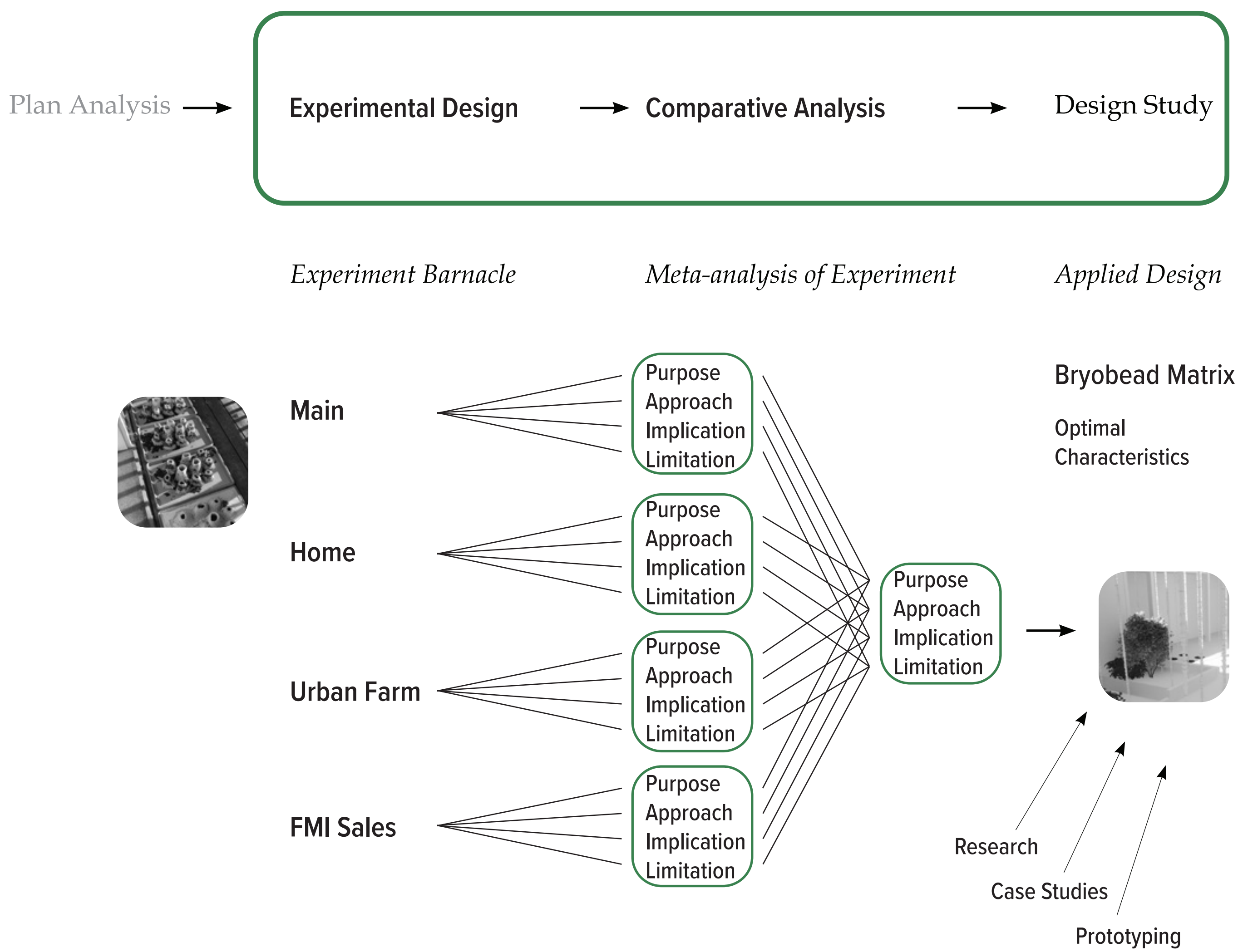


Fig. 3.0.2. Nijhuis and Bobbink framework of new knowledge cultivated through the process of experimental design and comparative analysis of the experiment to develop a final design.

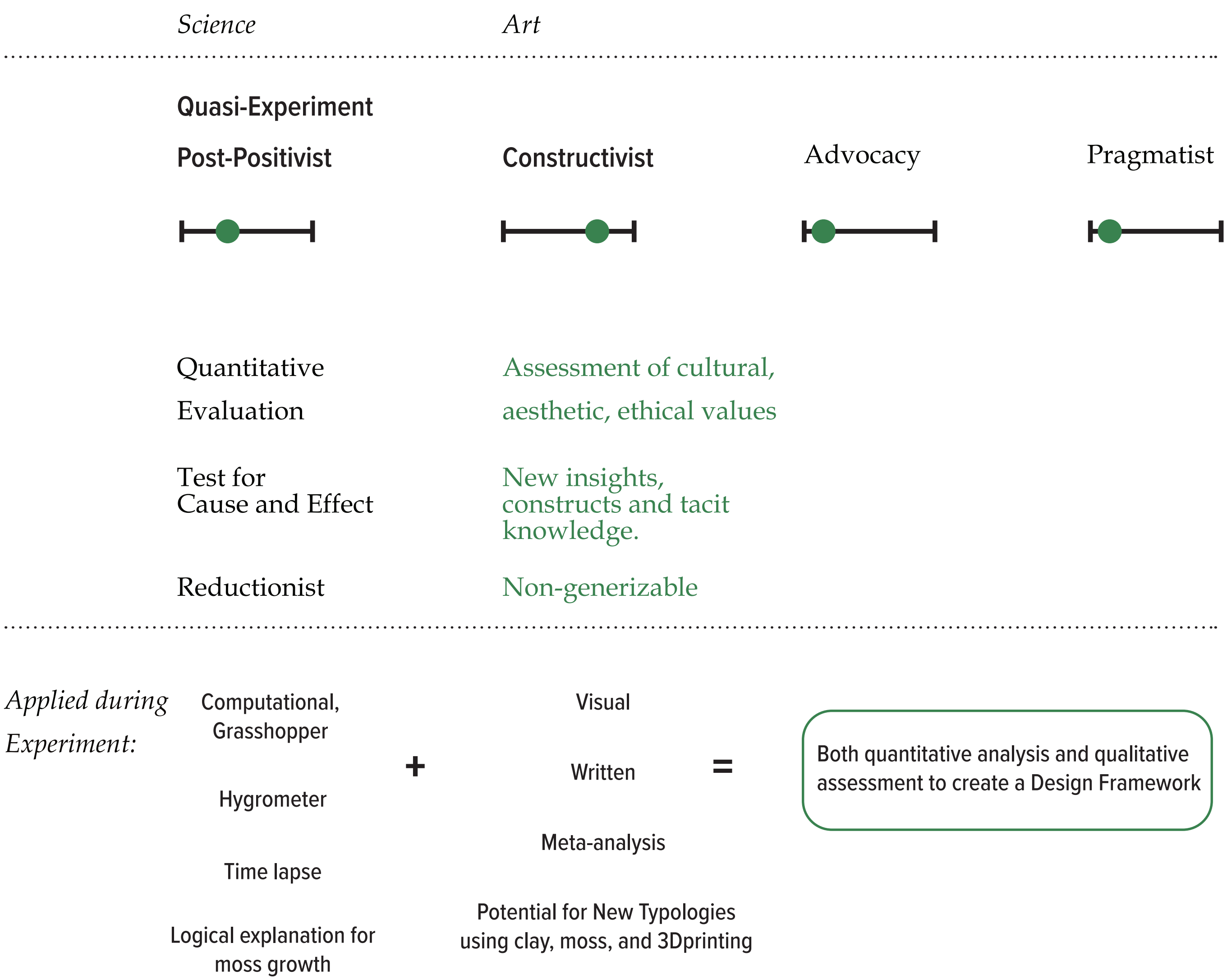


Fig. 3.0.3. The main part of the Master's Project falls under the Constructivist category under Lenzholzer's Research through Design methodological framework (Lenzholzer 2013).

Deming and Simon Swaffield in Landscape Architecture Research "research through design" is projective design. This type of inquiry is treated as purely subjectivist (Deming and Swaffield 2011). The range of research strategies spans the inductive strategy of beginning with experience to generalize towards a theory. This shows that something is operative, and the deductive strategy logically predicts an outcome and proves that something may be tested through experimentation. Because different methods have been used in this work through observation of the experiment and most likely conclusions are determined, this Master's Project is reflexive and abductive as seen in Figure 3.0.4. Design-based research is a process of abduction, of investigating what might be based on analysis of precedents. The Deming and Swaffield framework also encompasses an objectivist position of methodological emphasis associated with the natural sciences in contrast to a subjectivist approach associated with the humanities of celebrating new concepts. This work falls into the constructionist strategy bridging both ends of the objectivist and subjectivist spectrum integrating information through interpretation in formal analysis. The strategy for understanding research-through-design through the framework of Deming and Swaffield is slightly restrictive. Lenzholzer describes research as a systematic activity for generating new insights across disciplines that include four knowledge claims in research theory: post-positivist, constructivist, advocacy, and pragmatic. Each claim has a different aim, and the distinctions between them are often blurred. The post-positivist view is aptly named as it rejects the strict objective of arriving at a quantifiable truth through scientific investigation and pure objectivity. The post-positivist research worldview tests the physical realm and investigates the technical, functional, or environmental factors. The criteria for assessing post-positivist research include validity, reliability, and generalizability (Lenzholzer 2013). These approaches can be linked historically to the processes of research and development in industry. Groat and Wang explore "experimental and quasi-experimental" research, and again Deming and Swaffield address "experimental strategies." Deming and Swaffield situate their definition of experimental strategies in the pre-design phase. Because the approach of research-through-design generates general knowledge, it is partial knowledge and needs to be transferred to fit within a specific context for greater understanding.

Through the lens of research-through-design, it is possible to open the investigation towards addressing socio-cultural issues through contextualization through a constructivist research strategy. In landscape architecture, it is vital to address the physical and measurable effects of the environment and how this relates to interactions with humans. This constructivist approach is about generating new insights or constructs instead of testing them in post-positivist research. This work can be in the form of physical constructs for landscape architecture and urban environments. The constructivist work can follow the experimental and testing work to apply the design within a specific time and region. As part of the inquiry of the design, practice is the tacit knowledge of experienced designers, which is difficult to extract from the knowledge-generating process. Constructivist research asks questions about how the design might impact the experience of the community, for example, and hold the possibility to take on new metaphors, patterns, and new value systems. The method for developing new concepts relating to design through research is originality. The research needs to be clear so that it can be open to discussion and further development in and beyond the field of landscape architecture. This innovation in this constructivist research, as opposed to post-positivist research, is that the products may not be full designs and lack full functionality because this is not the focus of research-through-design process as seen in Figure 3.0.3.

As Lenzholzer implicates, overlapping research of post-positivist and constructive methods is possible and likely. Technical understanding of the function of something in the landscape can bring about change in the landscape. Using different strategies and evaluation criteria holds the possibility to enhance each other and arrive at more substantial outcomes. For example, in post-positivist research, testing specific prototypes through an experiment will produce more robust results, and the constructivist research will help build creative new solutions. These research processes can help bridge the utility gap between academic knowledge and applicability (Eliasson 2000) that works across disciplines. The potential to translate new research and design across fields leads to greater validity of the field itself in landscape architecture.

	Inductive (theory building)	Reflexive/Abductive (theory/practice interactions)	Deductive (theory reasoning)
Objectivist Strategies	*Description* **Direct Observation through Photography and Field Records**	*Modeling and Correlation* **Environmental Data tracking During experiment Computational Analysis**	*Experimentation* **Quasi-Experiment**
Constructivist Strategies	*Classification*	*Interpretation* **Formal Analysis of Changes in Experiment Framework Development**	*Evaluation and Diagnosis*
Subjectivist Strategies	*Engaged Action* **Pop-Up Exhibition**	*Projective Design* **Design through Research Typological Studies**	*Logical Systems* **Patterning, Final Design**

Fig. 3.0.4. The core of the Master's Project falls under the Abductive category under Deming and Swaffield's Research through Design methodological framework (Deming and Swaffield 2011).

Fall 2019

Moss Survey

Observe

Proto-Experiment

Microscope

Assessment

Summer 2020

Tech Set-Up

Firmware/Slicer

Grasshopper

Plug-ins

Gcode

Throughout

Research

Mosses

Ceramic

Digital Design

3D Printing

Bio-Design

Architecture

Landscape

Product Design

Experiment

Summer 2020

Case Studies

Survey

Highlight

Fig. 3.0.5. Timeline of preliminary research and topics addressed throughout project.

Phase One. The first phase of the Master's Project involved understanding the processes of mosses through visual survey and research. In the winter of 2019, during the Experimental Garden studio taught by Michael Geffel, the idea for the work was seeded while designing a 3D printed soil sculpture garden and questioned what might grow or interact on the sculptures over time. Considering what might grow on hardened substrate over time in the Pacific Northwest led to an interest in mosses and their benefits. Research began in the fall of 2019 and included reading about mosses, surveying mosses in the urban environment, and setting up a moss propagation experiment in the backyard as seen in Figure 3.0.5. This preliminary work led to producing grooved ceramic panels through the slip casting process to set up an experiment on campus which came to a stopping point due to Covid-19 restrictions in spring 2020. This research additionally rests on tacit knowledge of working with clay and ceramics and extends to new territory in applied design through 3D printing to create ceramic substrate.

Phase Two. The second phase involved setting up the technology to use the 3D printer. With financial assistance through the Decherd Award, a Cerambot 3D clay printer was purchased. Setting up the printer involved uploading software to the printer to transform it into firmware. Through trial and error and the help of a Cerambot user and coder in early in fall of 2020, the printer was set up. To make designs for the printer to read, a slicing program called Simplify3D translated the digital model to realize the first prints. This work was developed during two independent studies, the first being in "3D Printing in Clay," advised by Stacy Jo Scott, Professor of Ceramics at the University of Oregon. The second independent study was co-led by Professors Mary Polites and Ignacio Lopez Buson. Their instruction guided the digital design and concept process of designing in Grasshopper, a parametric modeling program. Advanced 3D Printing with Grasshopper, co-authored by Diego Garcia Cuevas and Gianluca Pugliese aided this learning for understanding essential design development in Grasshopper. The design language from Grasshopper was soon able to be translated with a Gcode script generated by Aman Argawal. These resources allowed for a direct translation from the digital work to the Cerambot printer without using a slicing program. Precedent work in 3D printing and experiments was researched to look for intersections in how this work developed.

Phase Three. In conjunction with the second phase of learning to 3D print and develop concepts, a Research by Design studio taught by David Buckley Borden involved learning about the structure, lifecycle, and benefits of mosses. Different propagation methods were researched to build the execution and design considerations for the experiment. The digital prospect of the experiment forms was used to create speculative designs in the Amazon neighborhood in Eugene, Oregon.

Phase Four. The third phase of the Master's Project involved design development for the experiment and occurred during printing different forms concepts. Creating stackable, modular forms at the outset was of particular interest. The printed forms were unsuccessful until design advancement was achieved by creating a higher range of amplification from the base narrowing towards the top of each form, filleting hard corners, and figuring out a proper clay consistency. Interest in making the same form changed when considering making multiple forms to test with variability for the potential to generate more information during the experiment. A barnacle cluster concept was embraced that possesses interior and exterior surfaces with different slopes and heights. However, the forms fit together at the base in the digital context, but once printed did not fit neatly at the bases due to an automatic reverse translation. Ten forms were developed and were printed with clay and 7% moss, clay with 5% sawdust, and clay with 10% sawdust. These thirty forms and 26 process forms were fired at cone 07, a low firing temperature to increase porosity for holding moisture and serving as attractive substrate for moss attachment. One of the clusters remained unfired as clay to see which changes may affect the clay and mosses.

Phase Five. The fourth phase involved setting up and monitoring the experiment as seen in Figure 3.0.6. The reason for the experiment is two-fold: to confirm that mosses will grow on ceramic substrate and to identify how mosses grow on the ceramic substrate for design development. This research strategy involved observing the experience of the experiment to determine the most likely conclusion. Four sites in Eugene, Oregon were identified to test different amounts and types of ceramic and clay bodies against moss growth. The main experiment was conducted off

Experiment Set-Up

	Location	Substrate
Main	West Eugene, Residential	10 clay+moss barnacles 10 ceramic with 10% sawdust burnout barnacles 10 ceramic with 5% sawdust burnout barnacles 10 ceramic barnacles 26 ceramic process pieces
Home	South Eugene, Residential	3 ceramic process pieces
Urban Farm	UO, Educational	3 ceramic process pieces
FMI Sales, Trucks, and Services	West 11th, Industrial	3 ceramic process pieces

Fig. 3.0.6. Experiment set up with locations and number of barnacle interfaces.

Quasi Experiment

Group 1 →	Observation →	Treatment →	Observation
Group 2 →	Observation →	Treatment →	Observation
Main	Weekly plan, axon, and detail photos.Hourly time lapse capture. Hygrometer monitor 15 sec.Written documentation.	Weekly monitoring, tray water refill, and water vapor mist.	Final written and photographic analysis.
Home	Bi-weekly plan, axon, and detail photos. Written documentation.	Bi-weekly monitoring, every-other day tray water refill, and water vapor mist.	Final written and photographic analysis.
Urban Farm	Bi-weekly plan, axon, and detail photos. Written documentation.	Bi-weekly monitoring, tray water refill, and water vapor mist.	Final written and photographic analysis.
FMI Sales, Trucks, and Services	Bi-weekly plan, axon, and detail photos. Written documentation.	Bi-weekly monitoring, tray water refill, and water vapor mist.	Final written and photographic analysis.

Fig. 3.0.7. Experiment was conducted as a quasi-experimental set-up (Groat and Wang 2002).

Garfield Street on the deck of residential space. A combination of mosses including four known species, Didymodon vinealis, Syntrichia princeps, Antitrichia californica, and Ceratadon purpureus were harvested from a roof Corvallis, rocks near Patterson Street, and from a range of substrates near Lawrence Hall on the campus at the University of Oregon. The upper, green parts of the mosses were fragmented with a kitchen knife and blended with water into a slurry. Choosing water-only as the binder for attachment to the substrate was intentional to reduce altering the natural microbiome. The mosses were hand-applied from the slurry to the substrates of barnacle clusters.

The ceramic and clay forms were set in metal baking sheets and filled with water two inches high to convey water through the porous ceramic forms. At the main experiment site off Garfield Street, the first group is clay and moss, the second group ceramic with 10% fired out sawdust, the third group ceramic with 5% fired out sawdust, the fourth group ceramic-only, and the remaining of ceramic only-process tests that did not conform to the barnacle forms. The trays were refilled with tap water every week, sprayed with water, and documented through rephotography in plan and axon view and hourly through a timelapse setup at an axon level. The temperature and moisture levels were tracked using a Govee monitor for eight weeks of the experiment. All three other experiments were set up simultaneously with three ceramic-only forms in baking sheets the similar moss applications, received biweekly watering, and the same documentation in plan view with detailed documentation. The second location was a residential patio under a deck at a residential space off Patterson Street. This experiment was refilled almost daily and misted with water daily halfway through the experiment. The third and fourth experiments were checked on a bi-weekly basis for documentation and watering. The experiment on the Urban Farm at the University of Oregon was placed on a metal cart under a plastic canopy. The fourth experiment at FMI Trucks and Service off West 11th Street in Eugene was placed under a storage container and was composed of three process forms. The experiments are considered quasi-experimental designs as this was a non-randomized control-group pretest-postest design as seen in Figure 3.0.7. All the groups received similar treatments and observations as randomness was not controlled. Alternative explanations cannot be ruled out, so therefore this is a quasi-experimental design.

During the experiment, case studies were identified that interrogated 3D printing, moss propagation on ceramic substrate, and ceramic applications in architecture. During a clay 3D printing class, this research employed a more advanced printer, the Potterbot, model 7. The printer was able to build larger objects faster and print with drier clay, which allowed for the development of more complex design work. The first iteration of rapid-prototyped work explored the typology of a rain screen and the advantages and disadvantages of creating a rain screen using ceramic and mosses. 5.5 forms were produced from the rapid prototyping work of exploring grooves and flat surfaces. Developing a rain screen seemed unsuitable in this context as rain screens serve to move moisture away from the building, and this project seeks to design substrates that hold moisture for propagating moss. The subsequent rapid prototyping work explored designing for the freestanding system of a two-sided wall. The six rapid-prototyped pieces extend more closely from the information gleaned midway through the experiments. This included designing practical elements such as an increased surface area with pockets to create shade, hold mosses, retain the grooved texture, and create stackable forms. These vertically stacking forms are held in place with a pipe and repeated to create a two-sided screen system to create a greater impact and flexibility in urban spaces.

Phase Six. The process of rapid prototyping to printing is a translational process from the idea that previously started from analog drawing to digital and physical form and experiment. This subsequent work considered drawing directly with clay through the traditional method of coil building, emulating the previous weaving inherent in the rapid-prototyped work. After building the woven sculpture that could be conceptually stacked, the form was photographed from seventy close vantage points. These photos were stitched together in Meshroom to generate points of the geometry. This work was then built into a mesh and texture within Meshroom and exported into a obj. file to be imported to Rhino. The mesh was trimmed in Rhino and then printed with the Cerambot on a smaller scale. This approach was a rich practice in translating an old art form into an emerging digital 3D clay printing process that shares similar construction methods. This work provokes new ideas in translating existing geometry that hold mosses through the

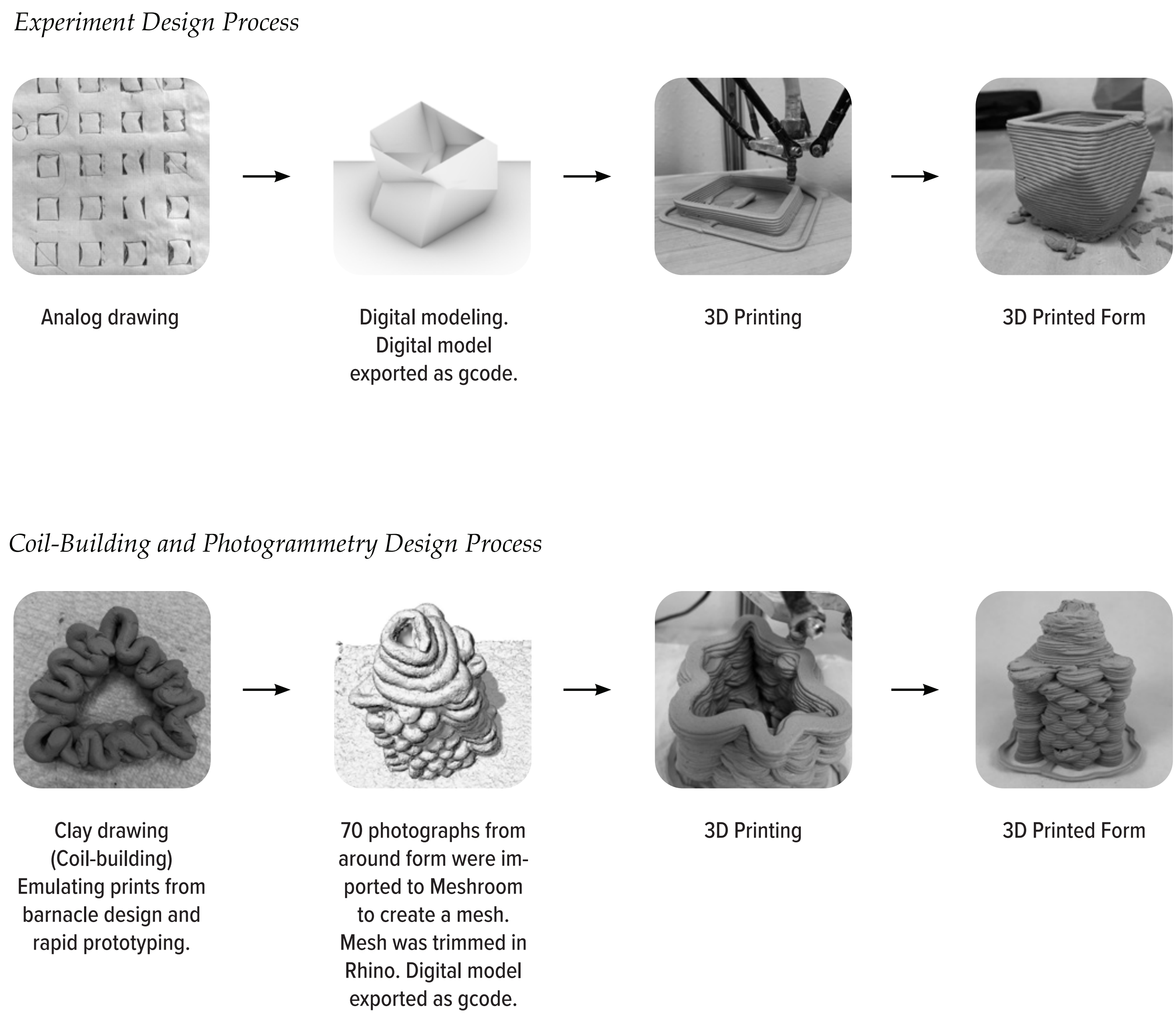


Fig. 3.0.8. Distinguishing differences between typical digital design process and coil-building through photogrammetry digital design process.

output of 3D printing to explore textures that would be difficult to emulate with parametric design in Grasshopper as seen in Figure 3.0.8.

Phase Seven. Returning to the use of the Cerambot printer with information cultivated during rapid prototyping, simpler beaded structures were developed to form a composition. This design development was an extension of the original barnacle experiment forms and the previously rapid-prototyped forms. The pieces went through another iteration of the rapid prototyping print process and design to make successful prints. Patterns were developed logically in sequences and analyzed individually and as a group for their impact in spaces. The experimental test sites were analyzed for their radiation and shade studies and compared against their success of moss propagation for determining suitable prospective sites for moss propagation. The final analysis of the experiment was brought forward into consideration for the final design work. This work was contextualized at a courtyard at Lawrence Hall, the design school at the University of Oregon, for its potential to create speculative design work in the form of the newly developed beaded and freestanding system. The translation of the work from experiment into a final design is a proof of concept that this work can be taken forward and adapted to exciting design work in the built environment.

Phase Eight. The final methodology involved disseminating this work to the public. Artifacts of the Master's Project were on view in "Foreground for Moss: Master's Project," one evening pop-up exhibition at the Hayden Gallery at the University of Oregon campus on the evening of May 20, 2021 as seen in Figure 3.0.9. This gathering exhibition offered the opportunity to share the meaning of this work through a brief talk. The content of the work showcased the results of the experiment, rapid prototyping work. This evening served as a platform for receiving feedback about the work in person and writing via a notebook. This final work as part of the University of Oregon's curriculum has been delivered during a public presentation and included in a PDF document.

Barnacle Interface → *Bryobrick Screen System* → *Bryobead Matrix*

Horizontal | Horizontal x Vertical | Horizontal x Vertical x Arrayed

Design typology output

Pop-Up Exhibition: Foregrounding

Community Engagement

Physical Experience

Collaboration

Feedback

PDF

Shareable Document

Presentation

Idea Sharing and Review

Feedback

Fig. 3.0.9. Diagram of evolution of design over time and final outputs of project.

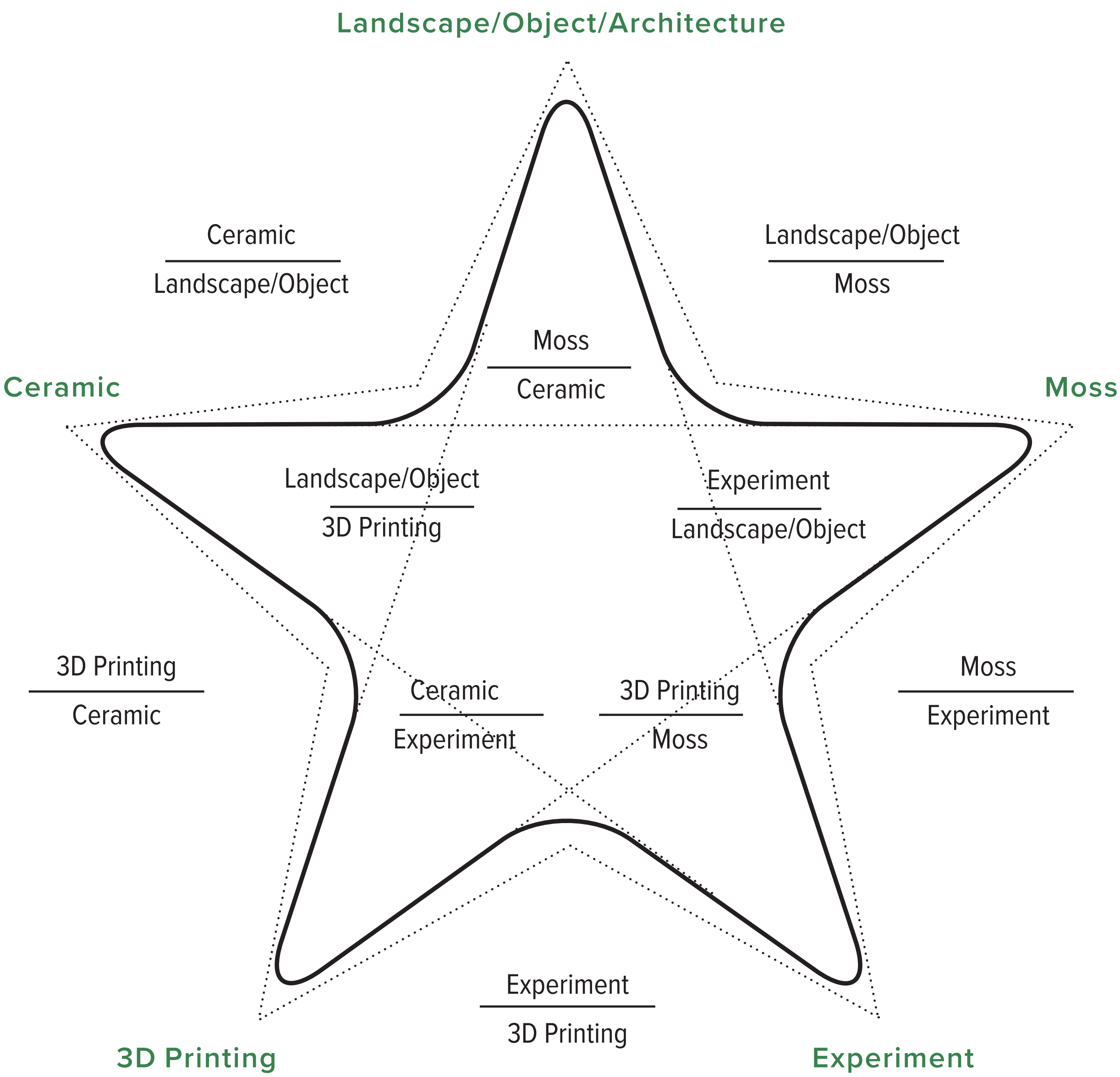


Fig. 4.0.0. Diagram of themes explored in case studies.

4. CASE STUDIES

At the outset of the Master's Project, I looked at various projects; these themes include ceramic, landscape, architecture, product design, moss, experiment, and 3D printing as seen in Figure 4.0.0. Throughout the research project, I learned about precedents in a scattered process. With a background in ceramics, I had a general idea of ceramic applications that exist in the landscape, such as roofs, tiles, and bricks. This knowledge was brought forward in a Design Development course focused on 3D printing and Grasshopper during Winter 2021. Through idea development and research, I identified a range of precedents that intersect most closely with 3D printing. There has historically been a strong link between architecture, objects, and landscape. I looked for intersections between these two themes with additional benefits such as evaporative cooling. Some of the precedents, such as Print Green by University of Maribor students and Pylos by IAAC Research, use soil in place of clay, so some terminology is closely connected but distinguished in the chart.

It was challenging to find deep research on most of the projects. There was only one project by Klarenbeek and Dros that integrated 3D printing for the moss precedents. There are several do-it-yourself experiments for propagating mosses; however, I chose not to include these experiments in this context as they relate less to design and lack strong validity. I decided to focus on four projects that resonated most closely with my work; however, they did not check all the boxes. Most of this work was executed in a research-through-design methodology and link to experiment through the generation of forms. Only if the project was explicit about the research and experimental approach did I check the box. These include Gregoire Gagneaux's thesis, "Brick Collecting Water Systems," Iker Luna's thesis, "Moss in Bio Ceramic System," Leslie Forehand et. al. Mashrabiya 2.0, and the University College of London's Biota work.

Designer	Project	Ceramic	LA/Architecture	Moss	Experiment	3D Print
Alma Bangsgaard Svendsen	Thesis Project at KDAK	X	X			X
Ammar Taher	Master's Research	X	X			X
Boston Valley Terra Cotta	Designing a Sustainable Green Wall	X	X	X		X
Brian Osborn	Surface F/X		X		X	
Brian Peters	Building Bytes	X	X			X
El Studio	Architecture and Research	X	X		X	X
Emerging Objects	Bad Ombres	X				X
EcoConcrete	Bioactive Wall System		X	X		
Klarenbeek and Dros	**Moss Structure N65**	**X**	**X**	**X**	**X**	**X**
FabClay	IAAC Research	X	X		X	X
Freeland Buck	Disaster Center		X			
MaP+S Group Harvard	Ceramic Morphologies	X	X			X
Green City Solutions	The CityTree		X	X		
Gregoire Gagneux	**Thesis: Brick Collecting Water System**	**X**	**X**			**X**
Grone Gevel Design	Green Roof Initiative		X	X		
Hyphen Labs	Moss Voltaics	X	X	X		
Iker Luna	**IAAC, Moss in Bio Ceramic System**	**X**	**X**	**X**	**X**	
Informed Ceramics	Multi-Axis 3D Printing on Molds	X			X	X
Jeff Schmuki	Nursery	X			X	
Jonathon Keep	Curve Series	X			X	X
Leslie Forehand et. al.	**Mashrabiya 2.0**	**X**	**X**			**X**
Lisa McDonald	Tiling Coral Reef	X			X	X
Katrin Zelger	Ceramic Water Filter	X				X
Matsys	The Seed	X	X		X	
Oliver van Herpt	Solid Vibrations	X			X	X
PEG	Not Garden		X		X	
Polymorph	The Weave	X	X			X
Pylos	IAAC Research				X	X
Sony Research	Bioskin	X	X			
Sverre Fehn	Eco House	X	X			
Terraplanter	Terraplanter	X	X			
Trumpf	Angular Variation	X	X			
UCL	**Biota**		**X**	**X**	**X**	**X**
University of Maribor	Soil Green		X		X	X
University of Waterloo	Material Syntax: 3D Printed Clay	X	X		X	X

Fig. 4.1.0. List of organizations and projects fitting into areas of concentration topics.

STUDIO ERIK KLARENBEEK AND MAARTJE DROS

Absorbing Architecture

Purpose

The N65, a major highway running through the Netherlands was set to be named the most beautiful and greenest national highway running through Brabant. Selected artists Klarenbeek and Dros addressed this issue by considering work that filters fine dust, reduces CO2 and noise by making architectural interventions that host mosses.

Implication

This infrastructure along the highway serves as test models for providing proof that the particulates are being absorbed and can benefit the Netherlands and show the potential to enhance transportation infrastructure on a global scale.

Approach

The interventions along the highway are composed of panels with frames. The structure is an open framework and allows light and air to pass through, filtering dust through the absorption of mosses. Through a range of geometries and locations for the experiments, alternative experiments, new approaches and methods are cultivated.

Limitation

There is limited information in English on the material composition of the structure and manufacturing process. The absorption tests thus far have shown to be lacking in efficacy.

Fig. 4.2.0. Case study of the N95 Prototype. Photo credit: Larenbeek and Dros. https://www.ericklarenbeek.com/ Site accessed: 5.19.21

FOREHAND, DOYLE, HUNT, SENSKE

Mashrabiya 2.0
3D Printed Ceramic Evaporative Facade

Purpose

To update vernacular architecture traditions and limitations in Mashrabiya designs with 3D printed ceramic assemblies. This work adapts the functions of standard Arabic lace screens composed of wooden parts that determine light filtration, airflow, and privacy primarily through of evaporative cooling.

Implication

The system was tested for the Mean Daylight Factor of ~17% exhibits an average reduction in solar performance. This system would apply nicely in dry climates and new construction or retrofits of buildings providing a variation of views. The ceramic facade can be integrated into the building's mechanical system and does not rely on rainfall for hydration. This architectural form is an affordable and performing alternative.

Approach

Three modules composed of a column, a truncated cone, and a hemisphere with a pattern that creates micropores on each unglazed ceramic form. Through the use of DIVA, an environmental simulation software, an optimal sun-shading structure was generated. The system was printed to scale at 42" x 42" in fifteen days and produced using a Potterbot 2.0. The pieces were connected through a stacking and punctured pipe system that mists water vapor saturating the ceramic forms to aid in evaporative cooling. Plastic flexible gaskets established greater stability between the pieces. This work was installed in a residential window for testing.

Limitation

The scale of the work was limited and was not tested with biota. The method of 3D printing manufacturing is relatively slow.

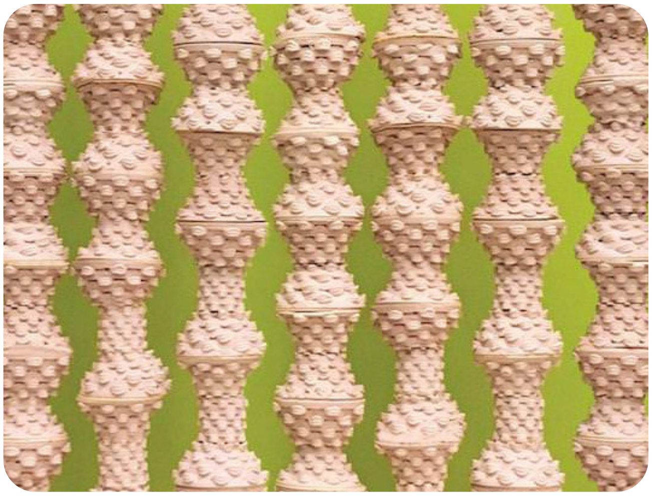


Fig. 4.3.0. Case study of Mashriyaba 2.0. Photo credit: Leslie Forehand. https://leslieforehand.com/portfolio/mashrabiya-2-0-3d-printed-ceramic-evaporative-facade/ Site accessed: 3.16.21

GREGOIRE GAGNEUX

Brick Collecting Water System

Purpose

This is a brick assembly geared towards optimally collecting rainwater that integrates with the building's internal pipe system for further use as greywater. Ceramic materials are able to filter water naturally through their water composition.

Implication

This work analyzes wind, solar, wind pressure, and wind orientation for applying this design to a large-scale facade. Applied on a larger scale of a high-rise building in Hong Kong, digital printing and robotics could provide greater energy independence to the occupants and lower environmental impact.

Approach

The forms of the brick were designed parametrically in Grasshopper from the development of wind and rainwater studies of the area to optimize the amount of collected water. Each brick varies in length, orientation, and shape to complete the whole of the assembly. The system's height can be up to two meters and three meters wide and span greater surfaces if attached to a concrete facade.

Limitation

The printing of the form requires mastery of each object, the digital design, printing, and assembly, rendering the production phase a
vulnerable process.

Fig. 4.4.0. Case study of the brick water collecting system. Photo credit: Gregoire Gagneux. https://issuu.com/gregoireggx/docs/portfolio_semester Site accessed: 3.16.21

IKER LUNA

Moss in Bio Ceramic System

Purpose

The bioreceptivity of moss in ceramics is explored in a range by creating different porosities to observe how water is retained, and natural fibers add beneficial qualities.

Implication

From this study, Luna determined that mosses can grow in ceramic environments with high humidity, good sun, and shade parameters. There is a heat buffer at the layer of moss and clay, where there is a moisture exchange between the moss and ceramic material. The porosity can be tested for sound and temperature buffers to serve as an example for a passive system.

Approach

Using an arduino microcontroller, Luna captured moisture data from within ten different regions inside the clay. Rock wool was added for structural integrity as high moisture levels can decay ceramic material over time. NIR and NDVI technology was used to understand which moss samples were more suitable for growing in controlled conditions.

Limitation

The limitation is that the different materials used depend on the environment they are in the climatic conditions. With mosses increasing the moisture and increased temperature to the material, the ceramic material can cause damage to a standard ceramic piece.

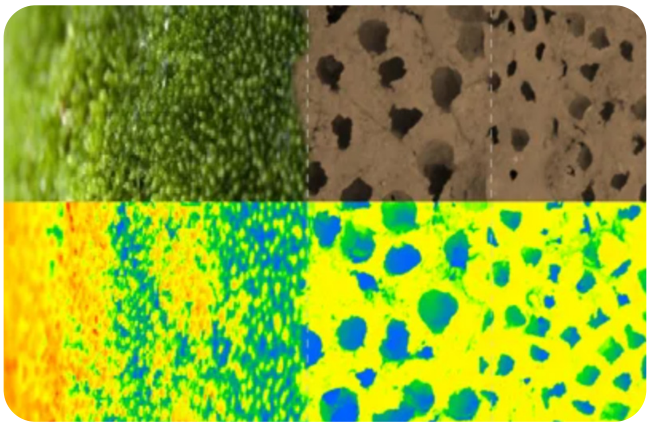


Fig. 4.5.0. Case study of Moss in Bio Ceramic System. Photo credit: Iker Luna. https://www.designboom.com/technology/iker-luna-experiments-with-moss-in-bio-ceramic-system-02-17-2014/ Site accessed: 3.16.21

ABIOTA, UNIVERSITY COLLEGE OF LONDON

Bioreceptive Concrete Facades

Purpose

The purpose of the design for these panels is to create bioreceptive panels that enhance the growth of cryptogamic species such as mosses, lichens, and algae.

Implication

This work serves as an alternative to green walls, which lack resiliency and require more maintenance. These biocolonizing facades increase the ecology of the environment and mitigate the effects of the environment by increasing green surface area and reducing maintenance.

Approach

Eighteen panels were created of three geometry types called Baroque, Poche, and Vertical. The cementitious panels were seeded in pairs testing the material differences between Portland concrete and magnesium phosphate. Using digital fabrication methods, surface morphology, and roughness, they aim to improve the facade performance. The pH levels, porosity, and water retention capacity has been integrated into the structure. They face the northwest aspect and, through photography and sensors, record biomass, humidity, and temperature.

Limitation

The study results are not accessible, so it is difficult to understand the outcome of this experiment.

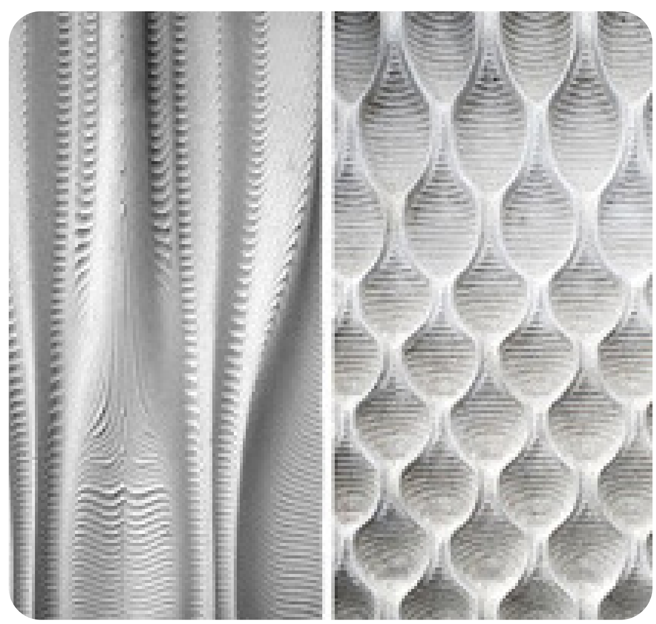


Fig. 4.6.0. Case study of ordinary Portland concrete with low porosity and high ph level. Photo credit: Marcos Cruz. http://marcoscruzarchitect.blogspot.com/2017/10/bioreceptive-concrete-facades-design.html Site accessed: 5.6.21

Fig. 5.0.0. Visual survey of images taken on campus at the University of Oregon.

5. DESIGN PROCESS

5.0 SURVEY OF MOSSES

During the fall of 2019, I first began to learn about mosses and began this through a visual survey by looking to see where mosses were growing near campus at the University or Oregon.

1. Mosses enjoy textured, porous, and concave surfaces where water collects and where mosses can attach their root-like rhizoids.

2. Mosses seemed to grow most abundantly near ground-level, however, there are moments on railings, on trees, and at the top of concrete walls where mosses trace the falling water as seen in Figure 5.0.1.

3. Different mosses seem to grow on different substrates.

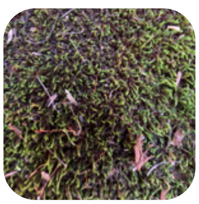
4. Some mosses grow with other species, and others developed as a monoculture.

5. Mosses grow on organic and inorganic substrates, occupying soft surfaces like the bark of a tree and soil and hard surfaces like concrete

Fig. 5.0.1. Orthotrichum sp. found growing on rock north of Columbia Hall

DIDYMODON vinealis

Moss observations on
UO Campus on concrete
near metal sculpture
east of Lawrence Hall



11.2.19
Temp: 39F
Humidity: 67%

11.9.19
Temp: 41F
Humidity: 87%

11.19.19
Temp: 43F
Humidity: 83%

11.23.19
Temp: 43F
Humidity: 91%

11.30.19
Temp: 36F
Humidity: 85%

12.7.19
Temp: 36F
Humidity: 92%

12.14.19
Temp: 45F
Humidity: 87%

CERATODON purpureus

Moss observations on
UO Campus on rock
near shaded walkway
south of Lawrence Hall

11.2.19
Temp: 39F
Humidity: 67%

11.9.19
Temp: 41F
Humidity: 87%

11.19.19
Temp: 43F
Humidity: 83%

11.23.19
Temp: 43F
Humidity: 91%

11.30.19
Temp: 36F
Humidity: 85%

12.7.19
Temp: 36F
Humidity: 92%

12.14.19
Temp: 45F
Humidity: 87%

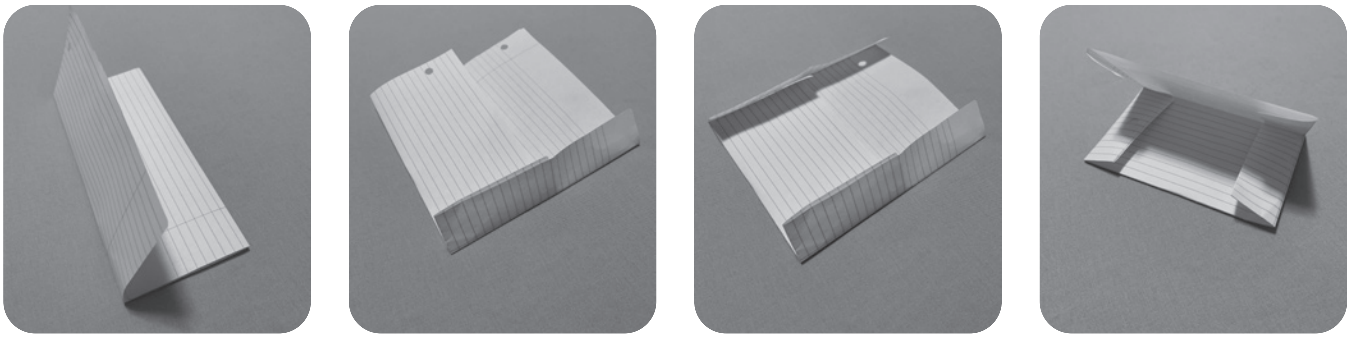
Fig. 5.0.2. Didymodon vinealis and Ceratadon purpureus monitored in relation to environmental conditions over time.

OBSERVING MOSSES

I identified ten sites on campus that I thought were different species of mosses. I took photos of the sites every week, taking note of the environmental conditions. The mosses were identified by Bruce McCune, Professor of Botany and Plant Pathology at Oregon State University. Didymodon vinealis and Ceratadon purpureus were two mosses that I considered for propagating on the ceramic substrate due to their adaptability and propensity to grow on hard substrate. I harvested Didymodon vinealis and Ceratadon purpureus for a preliminary experiment and blended the two mosses separately with water, yogurt, and vinegar. The experiment was first on the ground but was consumed by slugs. The blended mixtures were remixed and set vertically on the backyard fence but was perhaps monitored for too short of a time to notice moss growth as seen in Fig. 5.0.3.

Fig. 5.3. Didymodon vinealis identified under microscope.

Fig. 5.0.3. Proto-experiment monitored on fence briefly on 11.24.19, 11.30.19, and 12.8.19.



1. Fold 8x11.5" paper in thirds

2. Fold one side 1/6 inwards

3. Fold other side one side 1/6 inwards

4. Fold in half, label for safe storage

Fig. 5.0.4. Demonstration of creating an envelope for storing mosses.

Mosses are best stored in paper while in a dried state. Mosses are typically labeled with the species and georeferenced by the universal coordinate system.

Latitude and longitude are commonly used while federal and state agencies use University Transverse Mercator coordinates.

Fig. 5.0.5. iPhone Anglefly

Fig. 5.0.6. Compound Microscope (400x).

VIEWING AND COLLECTING

The identifying characteristics of mosses require examining mosses under the microscope. While observing mosses outdoors, I used an anglefly lens that pairs with an iPhone to take macro photography. At CAMCOR at the University of Oregon, I had access to a compound microscope where I took images of selected potential mosses to use in the experiment with amplification up to 150X as seen in Figures 5.0.8.-5.0.10. During the experiment, during the protonema phase, the first stage of moss growth, the mosses look filamentous. It is essential to take follow-up shots of the development post the experiment to verify that moss was indeed growing on the ceramic substrate.

Fig. 5.0.7. Macrophotography of protonema on experiment at FMI.

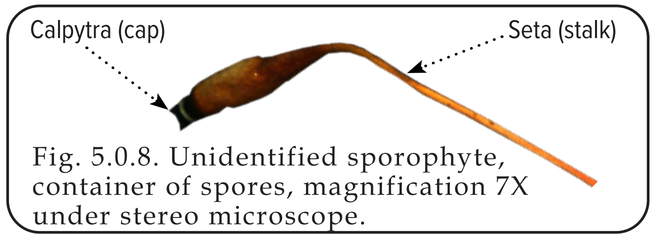


Fig. 5.0.8. Unidentified sporophyte, container of spores, magnification 7X under stereo microscope.

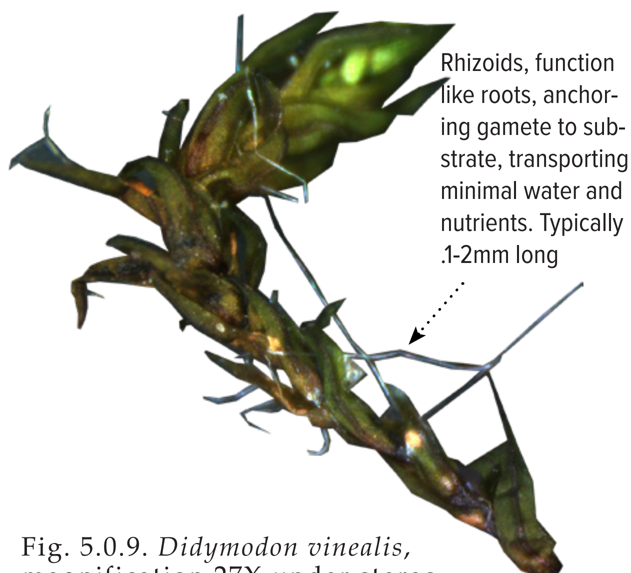


Fig. 5.0.9. *Didymodon vinealis*, magnification 27X under stereo microscope.

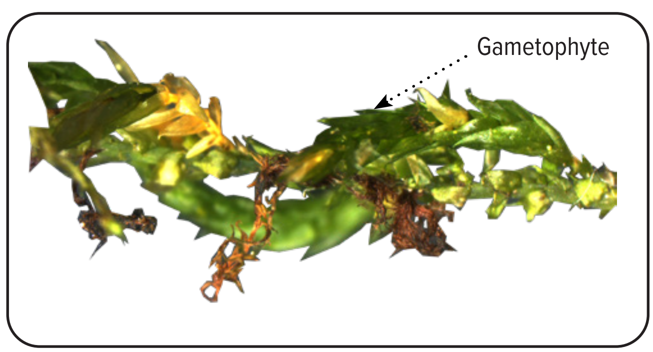


Fig. 5.0.10. *Kindbergia praelonga*, magnification 12X under stereo microscope.

MOSS REQUIREMENTS:

Light

- shade/partial light

Substrate

- porous for water retention
- hard or soft
- synthetic or natural
- grooved/rough surfaces in which rhizoids take hold

Elevation

- significant height unnecessary

DIGITAL INPUT:

Geometry (Rhino/GH)

- surface
- curve
- mesh pipe

Design considerations for printer

- soft angle change in plan (rounded forms
- slope of object slight for layers to build
- amplification of wall thickness
- for stability
- upright vessel forms dry more evenly than flat panels

Gcode

- slicer - Simplify3D
- grasshopper G-code

Design Workflow

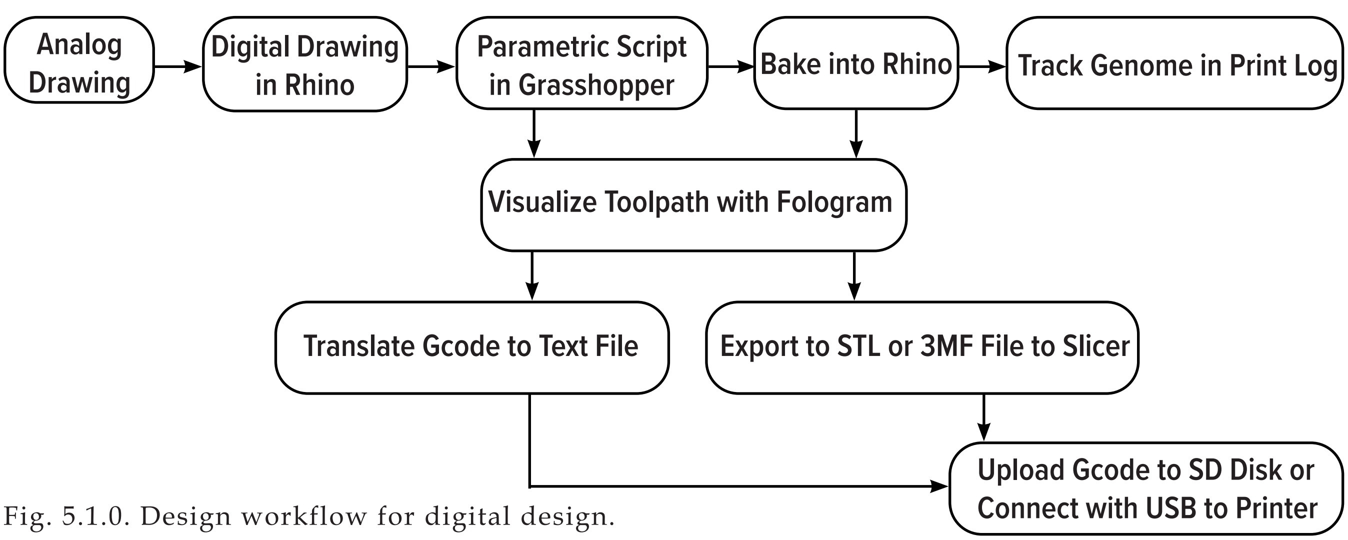


Fig. 5.1.0. Design workflow for digital design.

5.1 DESIGN FRAMEWORK

PRINTING:

Material
- G Mix Cone 6 dry mix (pH 6.7)
- pure clay
- 5% sawdust
- 10% sawdust
- 7% moss
- (self-mixing with refurbished Kitchen Aid mixer)

Material Impact
- compresses during printing
- gravity sags clay
- possible air bubbles
- expansion of curve from digital to toolpath
- reverse twist in expression of form
- shrinks 12% from wet to bone dry

Tools (retrofitted)
- 5mm nozzle
- silicone tube
- brass Fittings

Print Settings
- print speed at 960 mm/s
- extrusion speed
- layer height around 2mm
- voltage adjustment

POST-PROCESSING

Firing
- G Mix Cone 6 fired
- ceramic (pH 6.8)
- kiln type (electric)
- temperature
- bisque only underfire to cone 07 (no glaze firing or glaze)
- shrinks 12% during
- firing process

Materials - Moss Applications
- moss patch along grooves with hands
- moss slurry mix 5mm thick with water
  Ceratadon purpeus
  Didymodon vinealis
  Syntrichia princeps
  Antitrichia californica

Fig. 5.1.2. Design framework considering moss needs, digital input, printing limitations, and post-production.

Fig. 5.1.3. Possible tiling profiles in plan view.

INITIAL CONCEPTS

When determining my goal for the interface, one of the first ideas I focused on was identifying a tiling shape, and based on its rotation (1-6), figuring out possible assemblies in different configurations as seen in Figure 5.1.2. While this was a great exercise, it came to my attention that while the lines I was working with in Rhino tiled, the shapes would be unable to tile and interlock in a translated ceramic form. The inability to tile results because the ceramic material embodies more space than the perfect geometry of a line and would need to bend to interlock.

I realized that it was essential to return to observations from the visual survey and what I learned about mosses for determining design elements. I researched flora and fauna patterns that collect moisture, showing that channels, cone shapes, ridges, and grooves are important textures to consider for approaching a ceramic substrate design that best facilitates moss growth as seen in Figure 5.1.4.

FLORA/FAUNA | **SURFACE STRUCTURES**

Wildflower
Lampranthus hoerleinianus

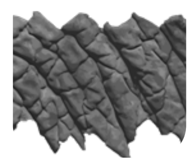
Rough Surface

Cactus
Opuntia microdasys

Conical geometry and grooves

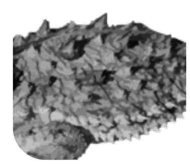
Elephant
Laxodonta africana

Ridges, Grooves



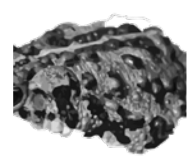
Lizard
Phyrynosoma cornutum

Honeycomb-like mcro-structure, channels



Toad
Anaxyrus boreas

Ridges, Channels



Wharf Roach
Ligia Exotica

Channels between hair and protrusion

Fig. 5.1.4. Precedent textures and patterns on flora and fauna that collect water.

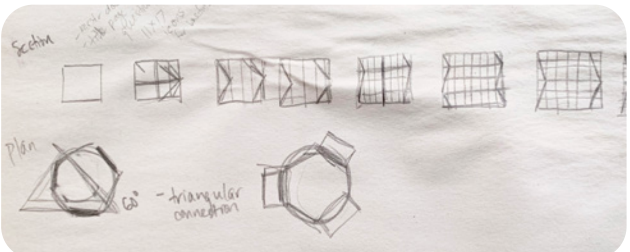


Fig. 5.1.5. First sketches for figuring out profile.

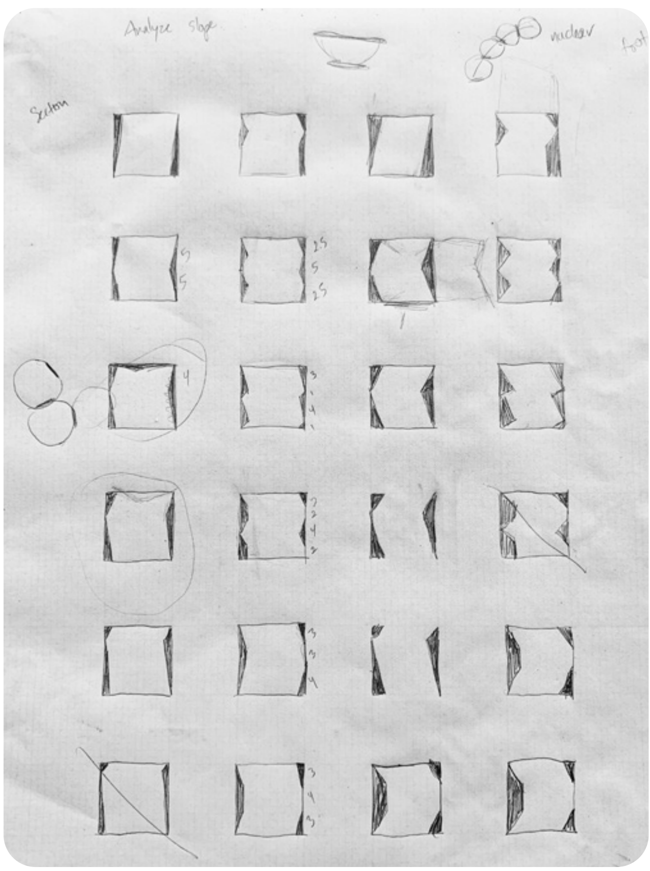


Fig. 5.1.6. Articulating section by units. Interested in change with 6 units from bottom and 4 from top and in forms that have one fold for structural purposes.

Fig. 5.1.7. Facets integrated into cylinder.

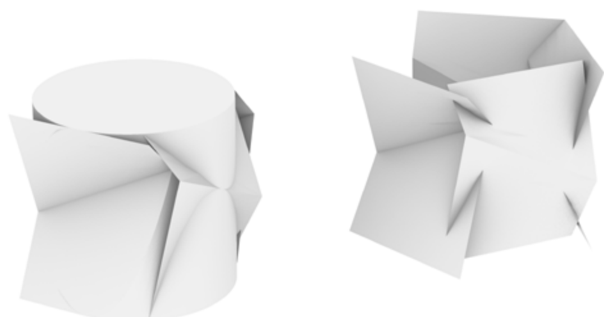


Fig. 5.1.8. Facets rotated to explore new form.

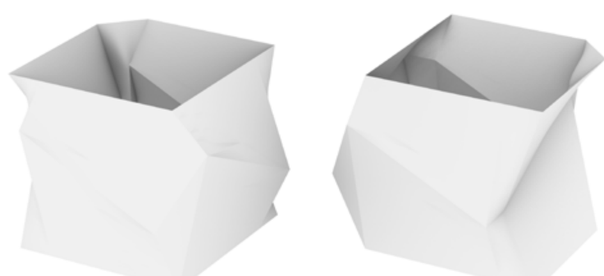


Fig. 5.1.9. Cube form with diagonal facets cylinder.

ANALOG DRAWING AND DIGITAL MODELING

Carrying work forward in designing a form, I was interested in the idea of continuing to produce work that tiled. Starting in analog, I drew silhouettes of tiles that I thought the printer could achieve as seen in Figures 5.1.5 and 5.1.6. This section looked like one unit indent 1 unit in of 10 and 6:4 unit indent from the base of the brick.

In Rhino, I started with a cylinder and made opposing cuts so that the form could tile. This iteration resulted in a boring-looking cylinder. I played with the cylinder a bit more but ended up using a cube form instead of a cylinder to continue to create with even geometries on all sides as seen in Figure 5.1.7. I took the indentation formerly straight from my drawing and made a crease at an angle by lofting the curves as seen in Figures 5.1.8 and 5.1.9. This shift allowed for a more dynamic look at the brick. However, the patched surfaces at the corners made for a random fix/
inaccurate solution.

Fig. 5.1.10. Cube form with sharp angles, top view.

Fig. 5.1.11. Cube form with abrupt corners, right view.

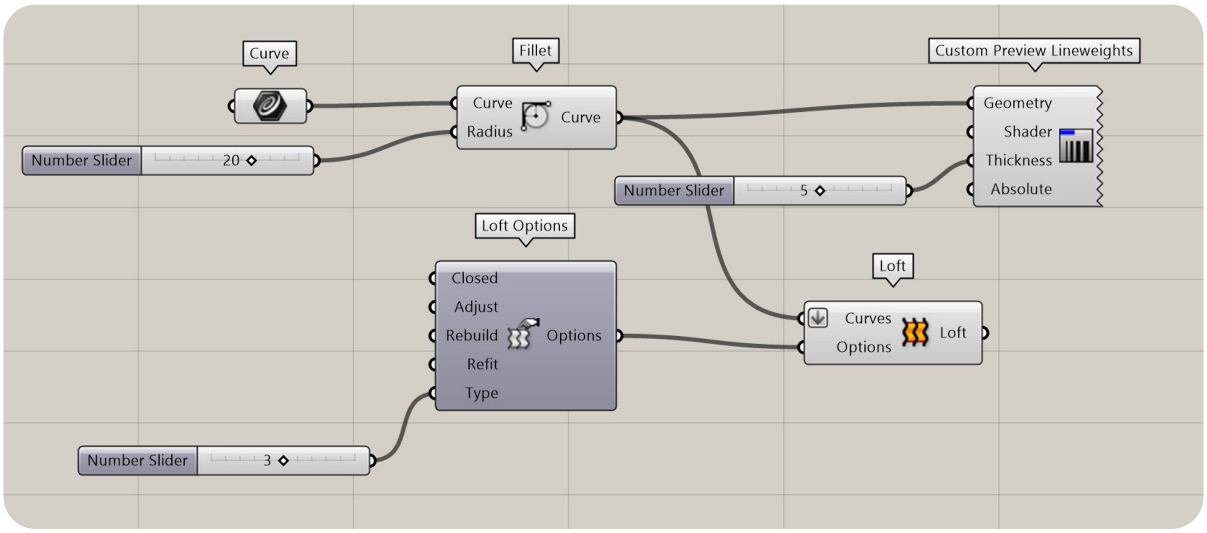


Fig. 5.1.12. Grasshopper script for designing lofted forms.

Fig. 5.1.13. Two forms that did not tile properly.

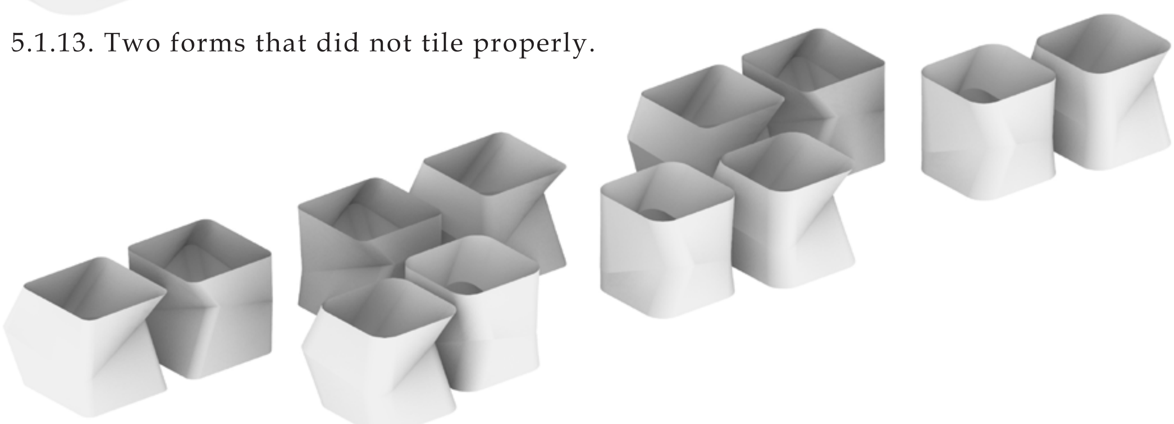


Fig. 5.1.14. Exploring form tiling with variables of 15 amplification and 20 degree rotation, 20 amplification and 20 degree roation, and 20 amplification and 15 degree rotation.

GRASSHOPPER

Taking the form from Rhino and into Grasshopper allows for smooth adjustments of the design. I used a script to loft three curves and smooth the corners; however, I found that tiling the bricks was not as easy to control. Once again, the script was taken forward in a different way to incorporate the indentation that I explored earlier as seen in Figure 5.1.12. However, the tiling did not seem to work three-dimensionally without rotating the bricks. This design work happened when the printer was down, and I was unable to test print to see the results.

I practiced "Advanced Grasshopper 3D Printing with Grasshopper to gear up for designing in Rhino and using Grasshopper as a plug-in for parametric design. This is the only book that I could find available to guide digital design specifically for 3D printing with clay. The authors Diego Garcia Cuevas and Gianluca Pugliese present a thorough introduction from understanding the materiality of clay, approaches to digital production focusing on 3D clay printers, and digital design using Grasshopper for 3D printing. Essential definitions in understanding clay, code, and digital are presented. There is a range of Grasshopper definitions covered showing different ways of using the components for different outcomes to generate designs that clearly articulate the toolpath of the nozzle. The book emphasizes the possibility of creating g-code within Grasshopper and sending it straight to the printer (without using a slicer). The instructions for the book are made for a WASP 3D clay printer while I am working with a Cerambot. A large part of my goal in reading this book was to ensure that I would be able to directly translate work generated from a curve or polyline from Grasshopper into gcode for the Cerambot (to skip the presume to smooth part of the slicer) to have greater control of the toolpath as seen in Figure 5.1.15.

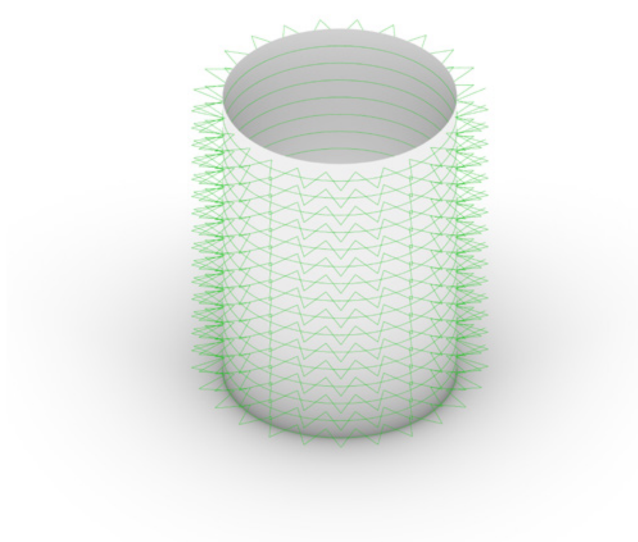


Fig. 5.1.15. Weaving exercise from a surface.

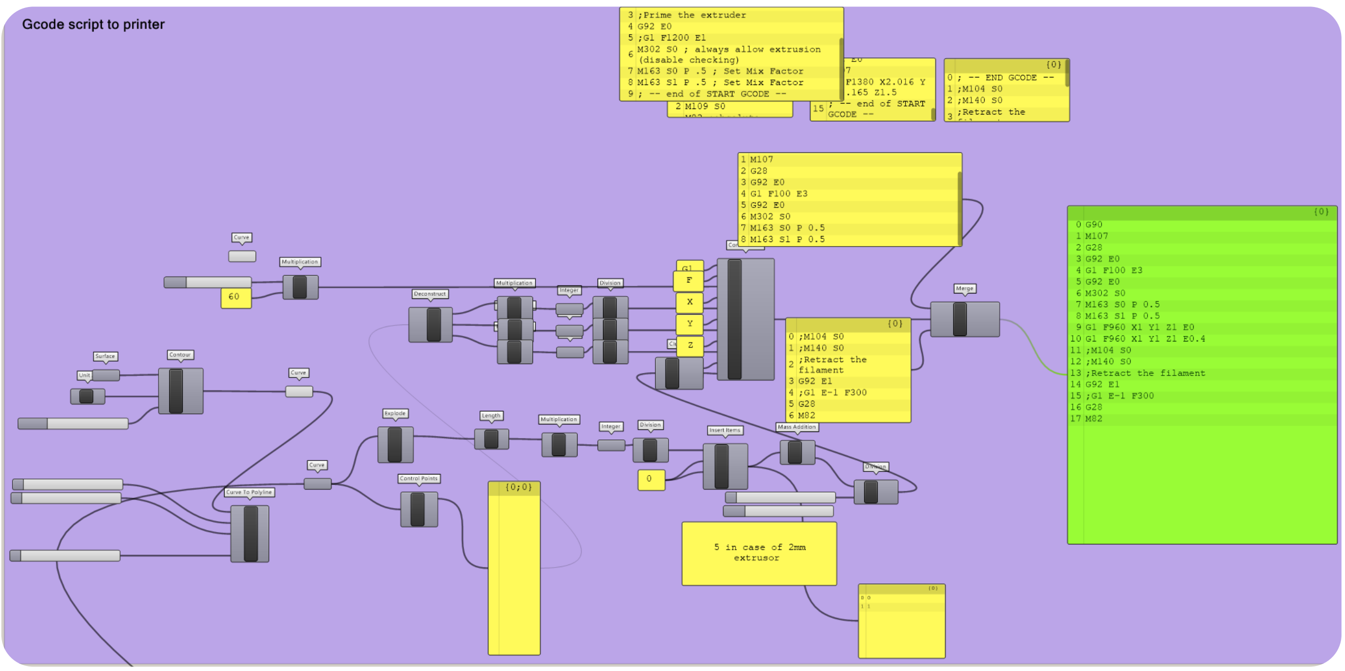


Fig. 5.1.16. Gcode producing Grasshopper script for printer to read.

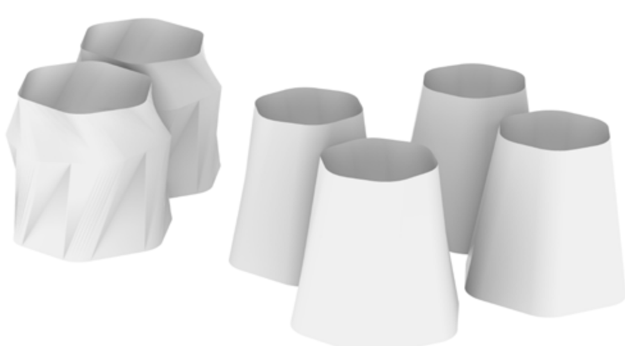


Fig. 5.1.17. Considering value of conical forms for water collection.

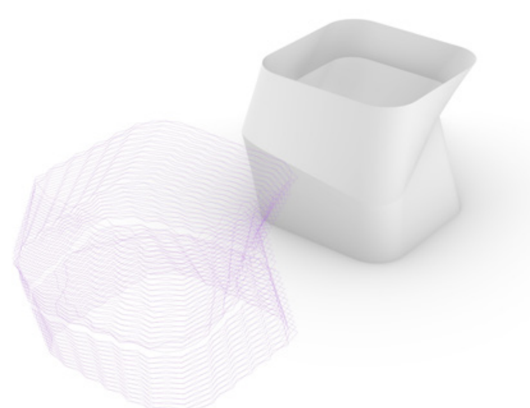


Fig. 5.1.18. First attempt at figuring out weave script for creating tool path.

ADVANCING CONCEPT AND CODE

During this iteration, I began to think more about the importance of creating a collection of varied surfaces as this would generate more information at this phase on which elements are optimal for propagating mosses. I created a grid of 16 vessels with filleted square apertures and circular apertures as seen in Figure 5.1.20. The heights were informed by an MD slider, forming a gradient of different heights and apertures. This function allowed me to directly translate the 3D model to the printer and have more control in investigating the surface grain. At this point, I was fortunate to receive a gcode script for the Cerambot from Aman Argawal as seen in Figure 5.1.16. With this opportunity, I learned how to apply the weave pattern to the form in the 3D Printing Grasshopper book to create a toolpath.

Fig. 5.1.19. Conical, curvilinar tiling forms.

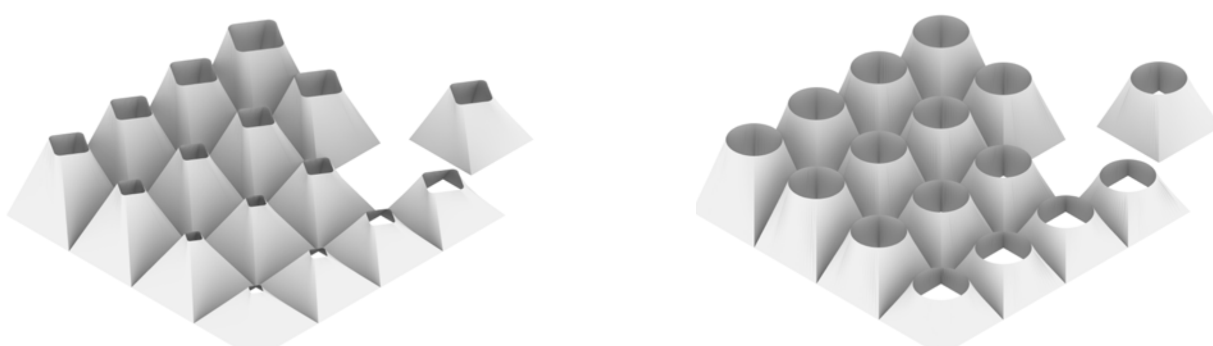


Fig. 5.1.20. Considering creating variability in a measured approach to generate more information from moss cultivation experiment.

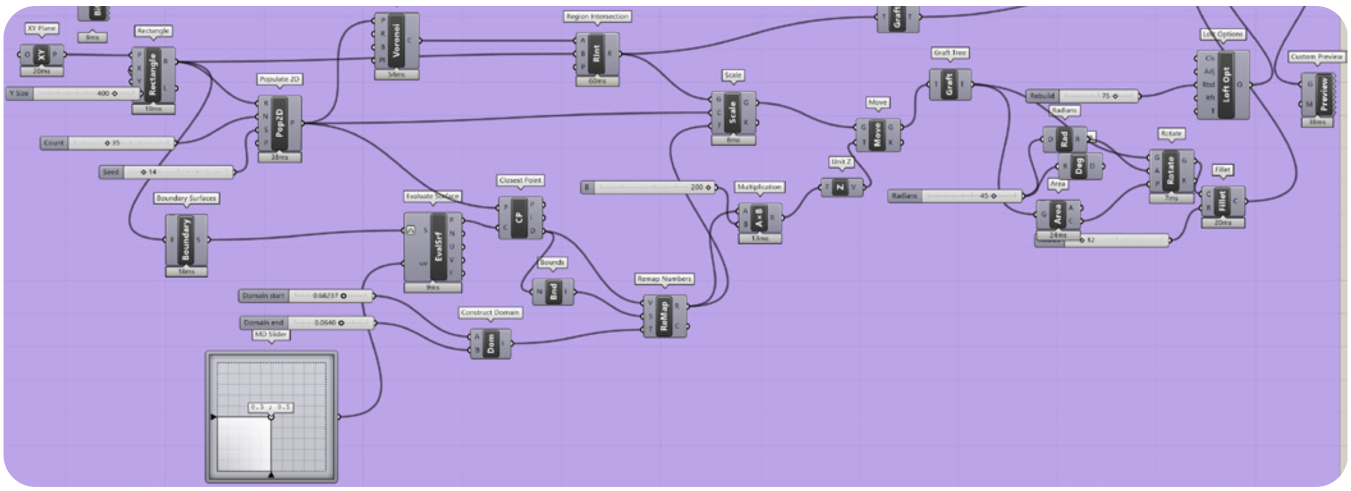


Fig. 5.1.21. Grasshopper script for creating barnacle/voronoi forms.

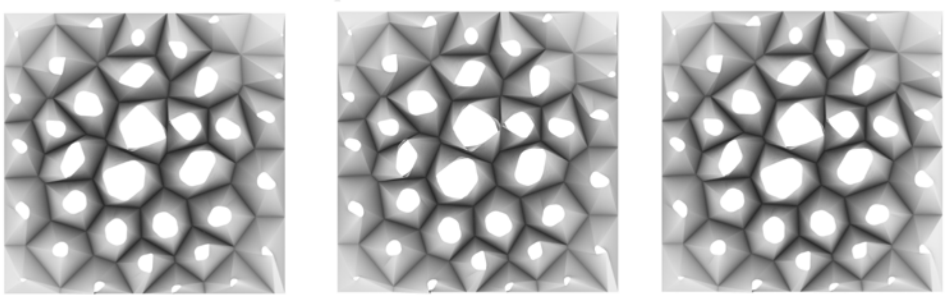


Fig. 5.1.22. Exploring fillet, aperture, height, and rotation for printing success.

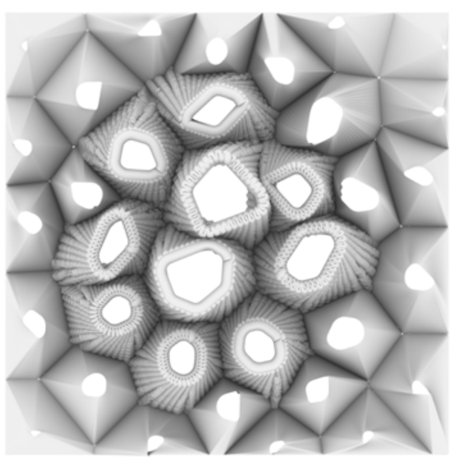


Fig. 5.1.23. Selecting optimal barnacles from group with greater slope and larger apertures.

INTERFACE: BARNACLE INSPIRATION

The prints derived from the grid square pattern were unsuccessful likely due to a combination of factors: the long toolpath, offset of the toolpath, and hard corners. I returned to the tiling theme, but of forms that had more sides, varying heights, slopes, and apertures similar to the arrangement of barnacles as seen in Figure 5.1.25. The collection and form are inspired by self-organizing barnacles adapted to life at the intertidal zone. Their structure attaches directly to the substrate, helping barnacles survive in hazardous environments.

Fig. 5.1.24. Found-barnacles as concept inspiration.

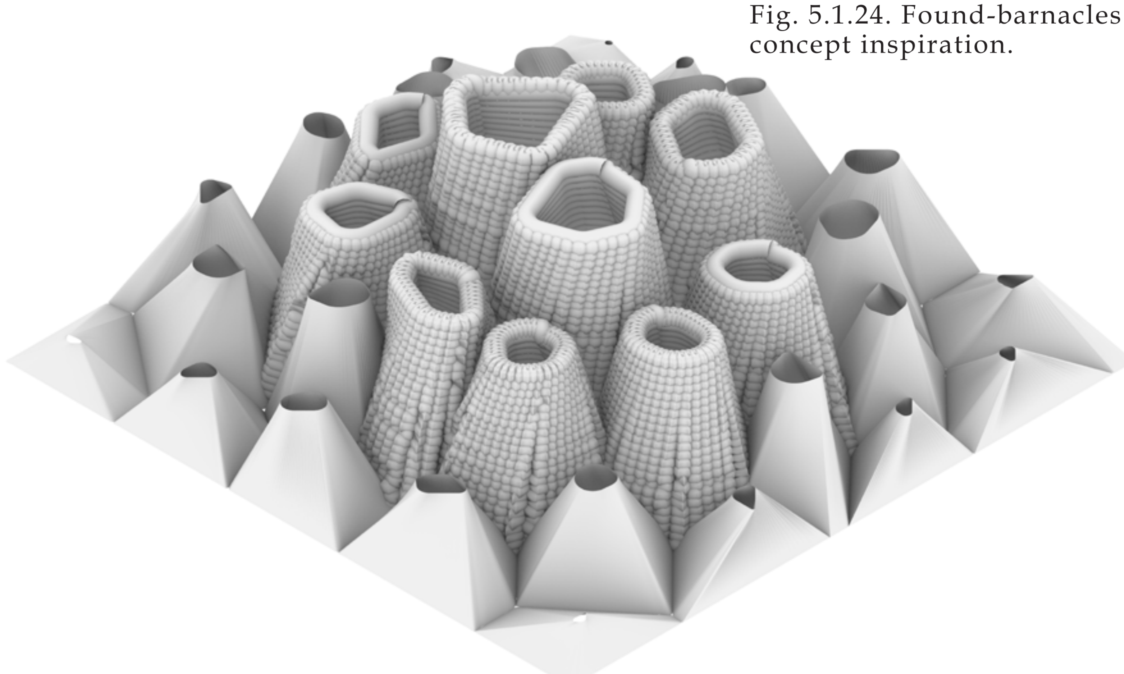


Fig. 5.1.25. Optimal barnacle cluster with 45 degree rotation from top to bottom.

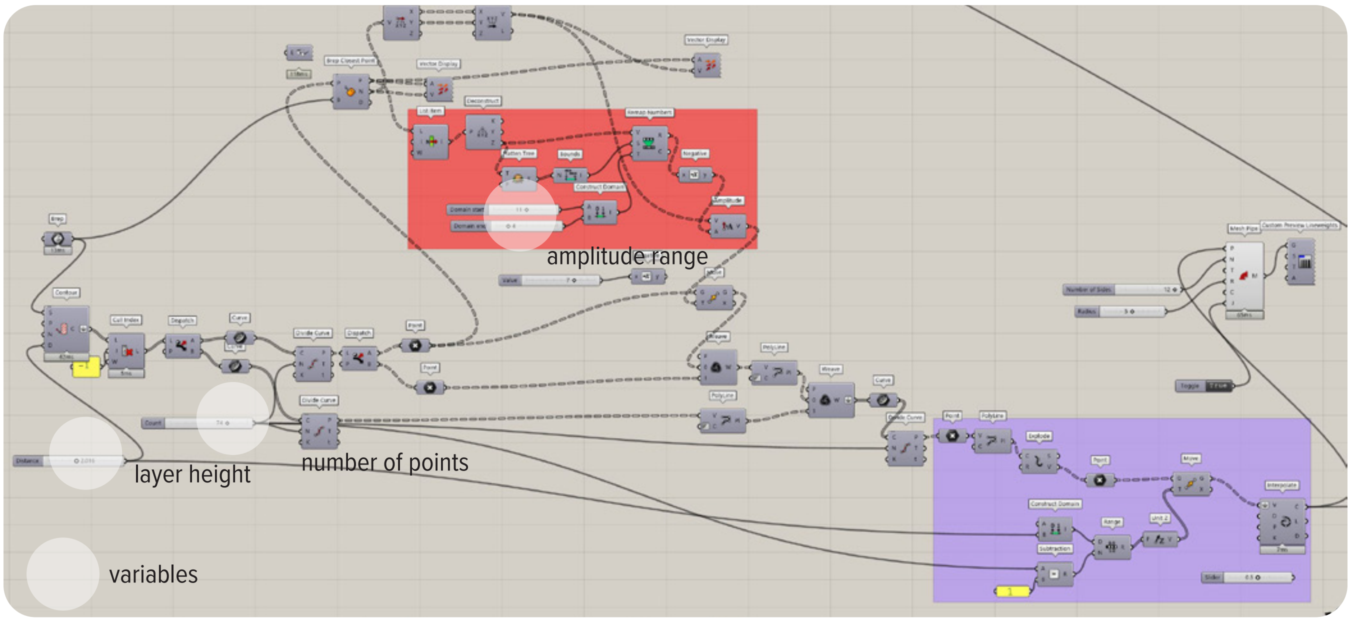
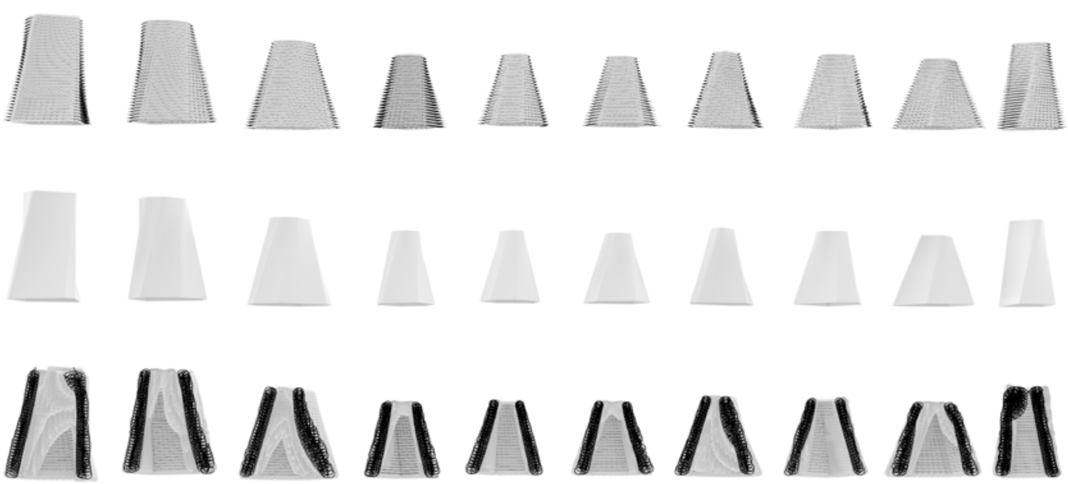


Fig. 5.1.26. Grasshopper script for generating woven texture on voronoi surfaces.



	1	2	3	4	5	6	7	8	9	10
Points for weave	76	76	74	74	74	70	68	70	63	63
Amplification, mm	3-10	3-10	3-10	3-10	3-10	3-10	3-10	3-10	3-10	4-11

Layer height 2.1mm for all

Fig. 5.1.27. Genome of ten unique forms for experiment.

10 INTERFACES

With further discussion and guidance from Ignacio Lopez Buson and Mary Polites, it was evident that the structural integrity of the form was off. Creating a range of amplification in the walls with greater thickness at the base towards thinner a wall at the top where support was necessary for success of the print, similar in how successful pottery is formed on the wheel as seen in Figure 5.1.27. Fologram, another great visualization tool was introduced to me called that expresses the diameter of the layer through a piped mesh as seen in Figure 5.1.28.

Bounding Box Dimensions

1	113 x 121 x 145 mm
2	126 x 115 x 139 mm
3	133 x 104 x 120 mm
4	110 x 108 x 107 mm
5	104 x 106 x 100 mm
6	109 x 101 x 100 mm
7	124 x 95 x 108 mm
8	112 x 125 x 106 mm
9	128 x 93 x 102 mm
10	87 x 103 x 125 mm

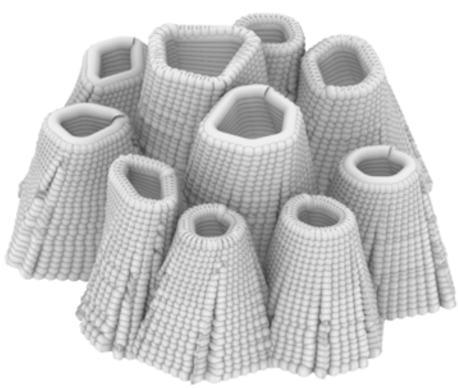


Fig. 5.1.28. Cluster dimensions: 305.450 w x 321.553 l x 145.23 h mm.

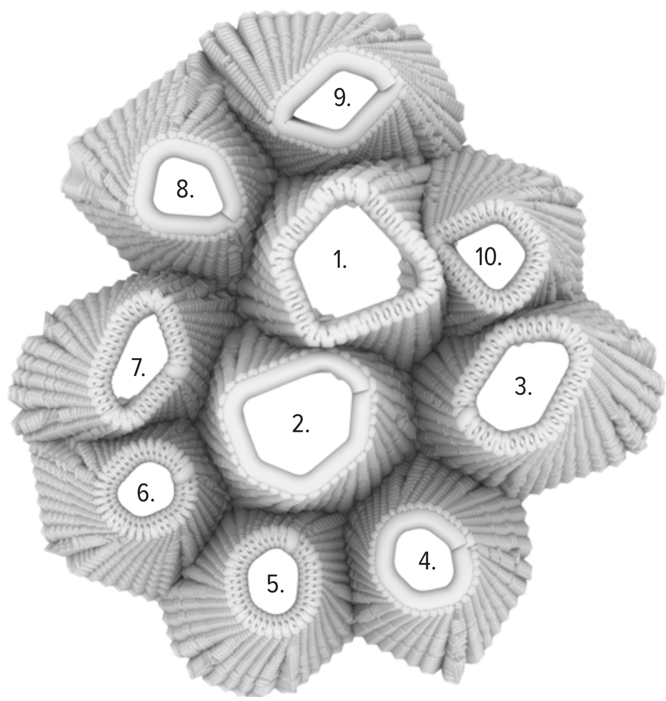
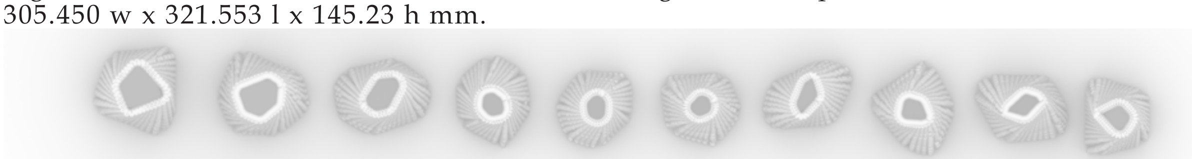


Fig. 5.1.29. Top view of cluster.



Mesh, top view:	1	2	3	4	5	6	7	8	9	10
Aperture:	5.5”	5.25”	4.5”	3”	3”	2.75”	3.75”	3.5”	3.5”	3.25”

Fig. 5.1.30. Genome data from top view.

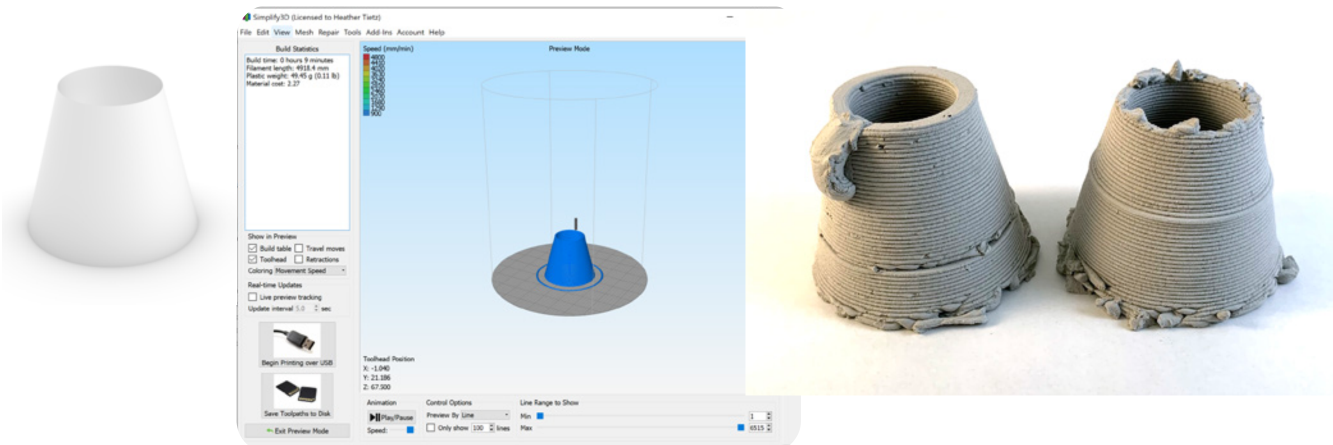


Fig. 5.1.31. First prints from simple design created in Rhino. Simplify3D, a slicing software translated the model from Rhino to the 3D clay printer Both prints experienced issues with adhesion to the print bed. The printer ran in hardware mode and kept extruding even though the print program ended. For the second print, the pressure building in silicone tube lessened the pressure at the nozzle and prevented the top layer from forming.

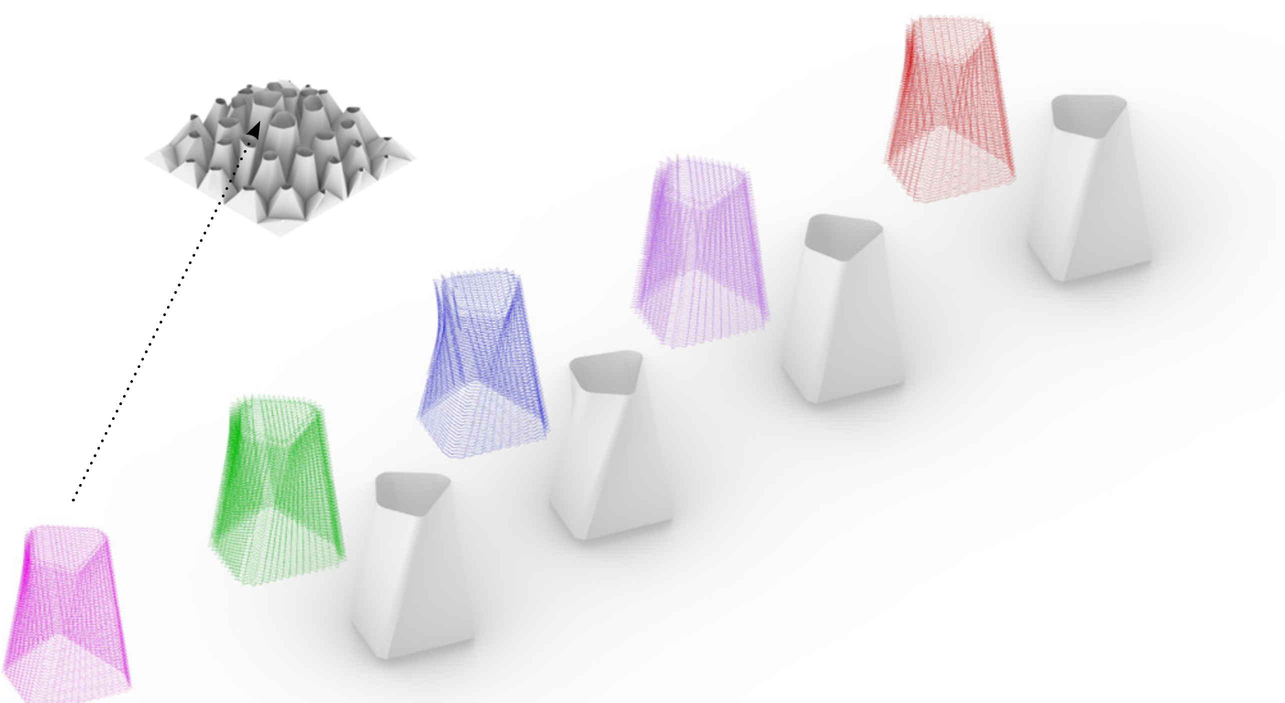


Fig. 5.1.32. Weave script and gcode script generated in Grasshopper, variations on amplification, layer height and speed of barnacle #1.

3D CLAY PRINTING

When first setting up the printer, I adjusted the parameters in Simplify3D to slice the model to generate the print. This program provided a simple output for creating stacked layers. By having access to the gcode, I was able to produce a successful print finally as seen in Figure 5.1.31. The gcode directly translates the model of the digital design to the printer. Without the translation of the gcode, the printer would not be able to print. It took months to set up the gcode properly to print!

I started by printing the largest and most central barnacle and tried different rotation degrees at the top, fillet, and number of curves. I selected the central taller barnacles with greater apertures because I wanted the slope to be greater for the success of the print and wanted the light to enter the interior spaces. This form kept collapsing and knew that I could not proceed if I was unable to print the central barnacle successfully as seen in Figure 5.1.33.

11.12.20

1.594 layer height, 75 divided curve (every other layer flat and zigzag, 9 amplitude of grain

11.14.20

1.5 layer height, 75 divided curve (every other layer flat and curved - interpcurve, 10 amplitude of grain (rotated 60 degrees)

11.15.20

1.5 layer height, 68 divided curve (every other layer flat and curved - interpcurve, 7 amplitude of grain (rotated 45 degrees)

11.15.20

1.5 layer height, 68 points, 5 amplitude, interpolate curve, rotation at 45 degrees

Fig. 5.1.33. Shifiting paramaters during rapid prototyping to arrive at a successs print.

Fig. 5.1.34. Saved 3D print succession from left to right, top to bottom. 10.10.20-11.26.20.

PRINTING PROCESS AND DETAILS

The printing process required numerous tests to learn about the optimal clay consistency and design for creating successful interfaces. The geometry of the ten interfaces was adapted with a woven toolpath to create a gradation in amplification unique to each form. The gradation in amplification is essential to the structure and as a variable for the experiment. Surprisingly when the printer translated the interfaces from the digital model, they rotated in the opposite direction, interfering with tiling intention at the bases as seen in Figure 5.1.35.

Fig. 5.1.35. Translation of cluster in 3D print. Note that bases of forms do not tile due to the opposite twist of what was modeled in Rhino.

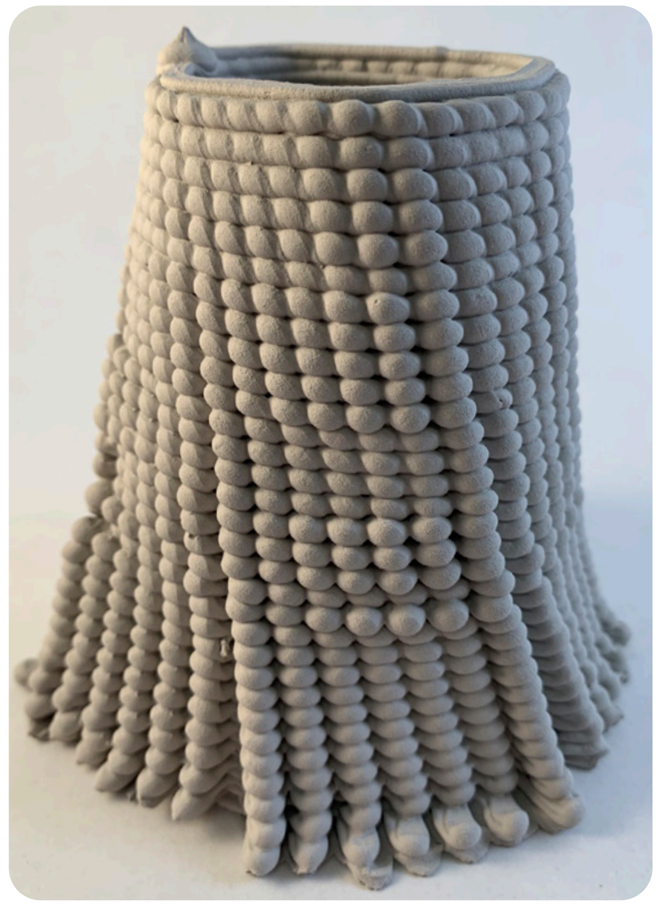


Fig. 5.1.36. Barnacle interface #2, amplification of weave.

- Fine grained texture
- Slight conical form for collecting water
- Grooves deeper at base create internal surface area
- Interior/Exterior surface for moss growth
- 3mm amplification at top
- 10mm amplification at base

3.
View
mic
awdust

1. 2. 3. 4. 5.

4.
mic

3.
mic
awdust

2.
mic
sawdust

1.
7%
s mix

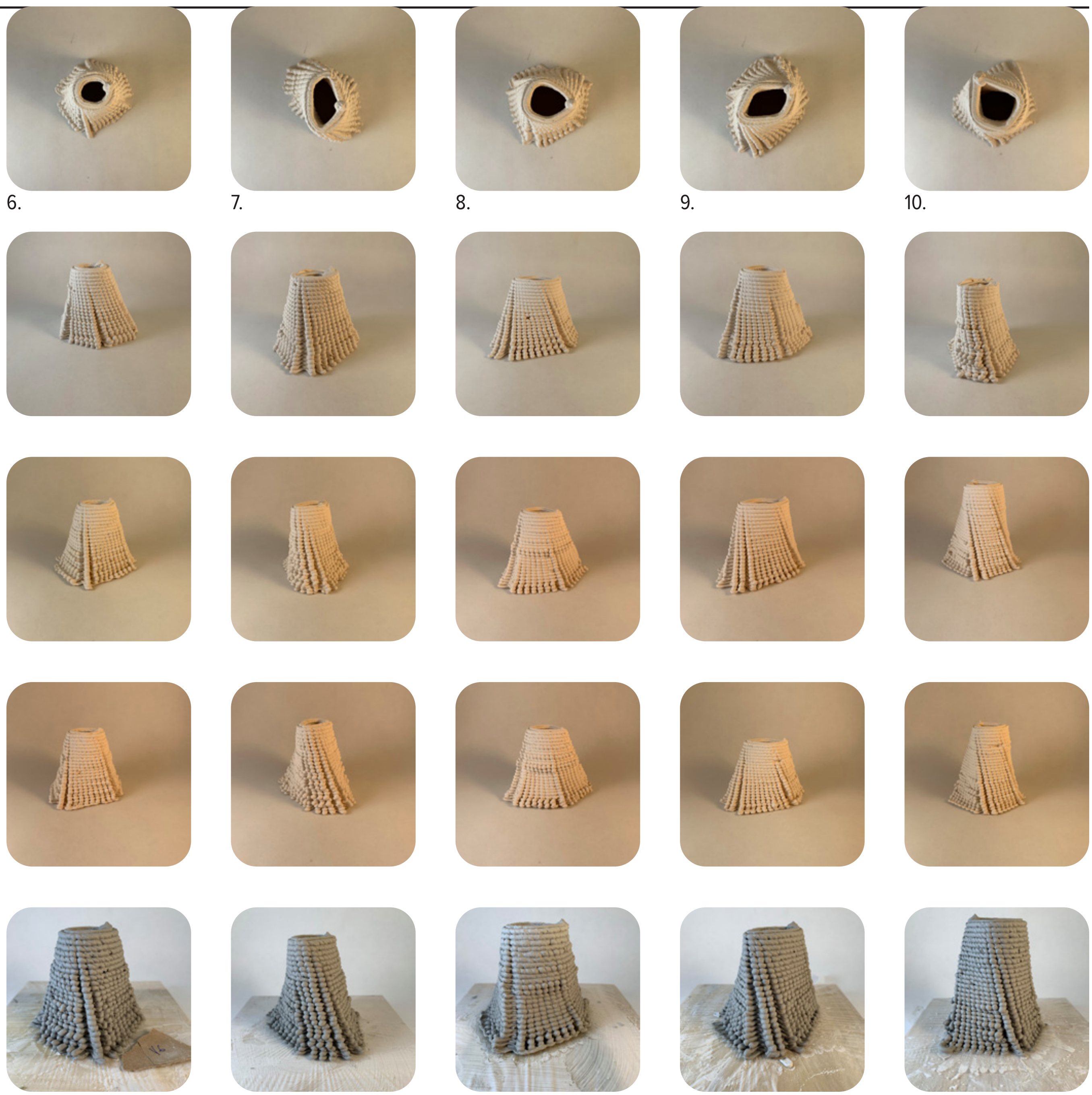


Fig. 5.1.36. Printed barnacle interfaces. See page 182 for post-experiment results.

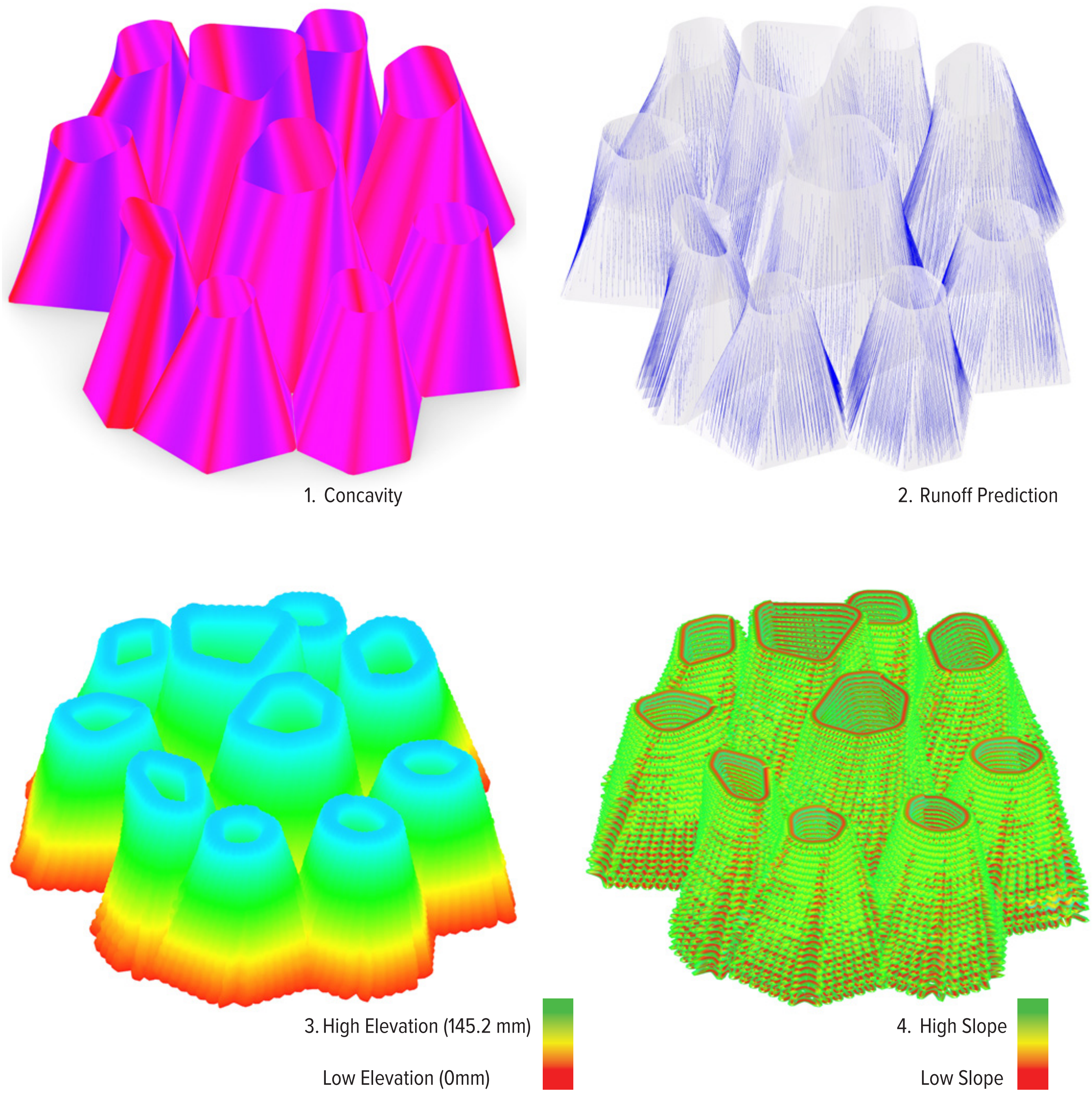


Fig. 5.1.37. Grasshopper analysis of barnacle interfaces.

INTERFACE ANALYSIS

Using Bison, a plug-in for Grasshopper, the color gradations show attributes of concavity, runoff, elevation and slope of the interface cluster as seen in Figure 5.1.37.

1. The concavity of the interfaces vary slightly with the greatest concavity showing purple and the least or convex aspects to the interfaces showing red. Around the 45 degree rotating rounded edges of the facets is where the least amount of concavity exists.

2. The relationship between the concave forms and the runoff is similar. Where the concave formations exist, the prediction for runoff is greater. Also, where the slope is less, the runoff is predicted to be greater. This study is only speculative for the experiment as the interfaces received only a misting of water vapor which behaves differently than direct runoff.

3. The forms ranged in size from 145mm (5.7 inches) to 100mm or (3.93 inches). The two tallest forms are interfaces #1 and #2 and are centrally located. The surrounding forms of #3 and #10 are the next tallest and #6 and #5 are the shortest of the interface collection.

4. The bison analysis measures the piped mesh of the interfaces, considering the angles of the fine grain of the texture. By looking at the fine analysis of slope, the lower slopes tend to fall near the base of each interface where the amplification is at maximum 10mm and along the rim. The highest slopes are where the weave has the least amplification of 3mm near the rim.

Fig. 5.2.0. Modified fittings and tube.

Fig. 5.2.1. Original extruder and tube and handy paperclip for unclogging nozzle.

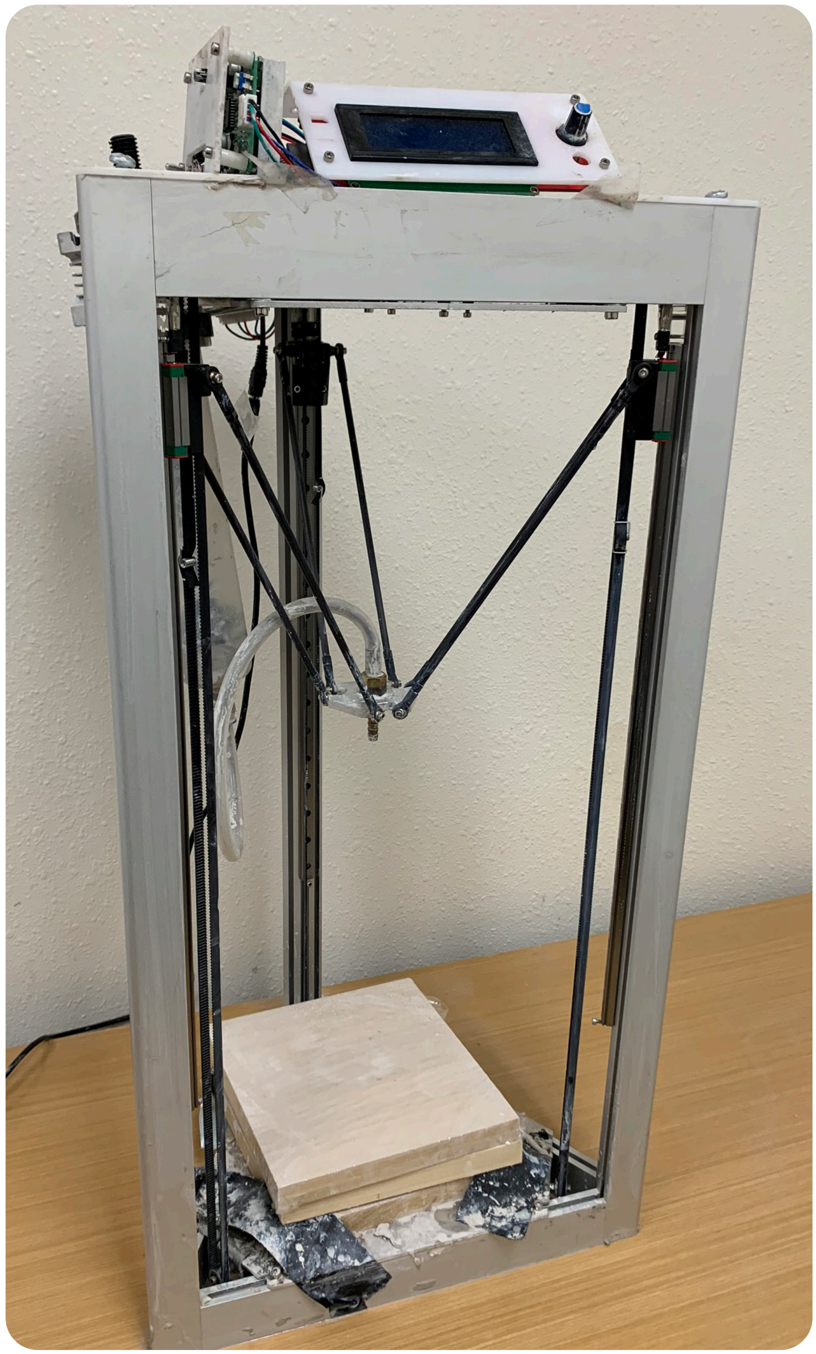


Fig. 5.2.2. Cerambot Pro Printer.

5.2 INSTRUCTIONAL DOCUMENTATION

Cerambot Pro 3D Clay Printer

Delta Printer (3 axis)
Build Volume 170 x 170 x 285mm
Nozzle Diameter: 5mm
Layer Thickness Setting: 0.5-2mm
Printing Speed: 5-50 m/s
Machine Dimension: 350 x 350 x 750mm
Connectivity: USB/SD card
Support Model Formats: .stl/.obj
Stepper Motor for Extrusion: NEMA 23

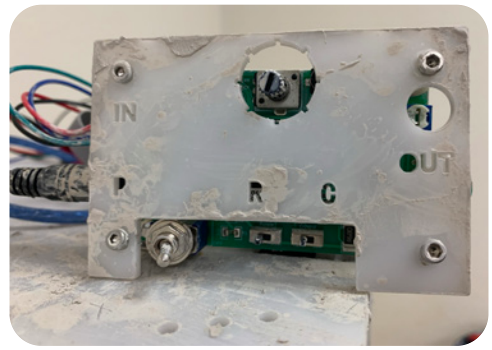


Fig. 5.2.3. Stepper motor control board with hardware and software options.

Cerambot Modifications:

1. Removed extruder and replaced with brass fittings on effector plate to create a 5mm nozzle instead of working with the default 1.5mm plastic nozzle.

2. (As per recommendation, have a range of plastic nozzle sizes (current 14-25 gauges) for altering if interested in reattaching extruder.)

3. Replaced hard plastic tube with flexible uxcell silicone tubing ¼″ (6mm) ID x 3/8″ (10mm) to seal around the brass fittings.

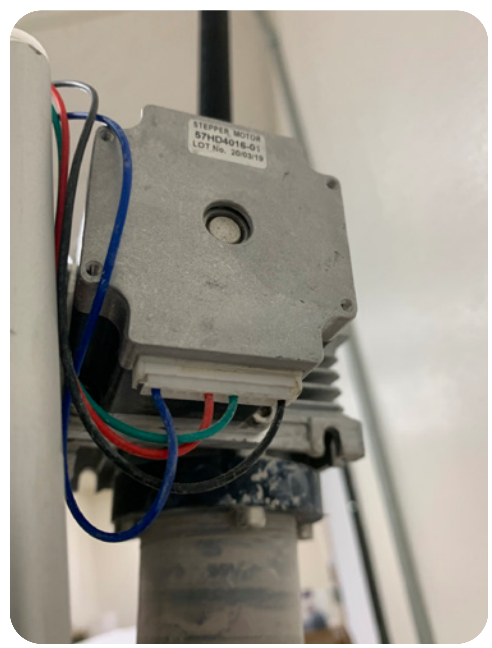


Fig. 5.2.4. 57 Stepper motor (NEMA 23).

Powdered G Mix Clay

Sawdust additive

mL Beaker for measuring water

Weigh dry clay in grams

Funnel for measuring ounces

Mix with kitchen mixer

Fig. 5.2.5. Tools and ingredients used for clay mixing process.

CLAY MIXING PROCESS

1. Measure water using a milliliter beaker and place into KitchenAid mixing bowl.

2. Weigh G Mix Cone 6 dry mix clay on kitchen scale and place into KitchenAid mixing bowl.

3. Add other additives such as sawdust from 1-10% composition of clay mixture (Optional: combine in ziplock bag to prevent dust during mixing.)

4. Mix on low for 15 minutes. Add dry clay and water as needed in 6:4 ratio to find toothpaste consistency application. Let clay sit for a few days before use for clay particles to hydrate.

5. Compress clay with spatula to remove air bubbles. Store tightly in bucket with lid for clay to hold moisture content.

Substrate Combinations

Clay (g)	Water (mL)	Sawdust (oz)	Moss (g)	Darvan
900	*400*	*10*		
2166	*1000*			*.5 tsp*
900	*400*	*10*		
867	*600*			
2639	*1180*			
1700	*3367*			
3184	*1700*	*8*		
2267	*1000*	*3.85*		
2970	*1500*	*15*		
1670	*800*	*8*		
3331	*1900*		*45.5*	
714	*400*		*10*	

Fig. 5.2.6. Substrate combinations for each batch mixed throughout printing process.

Fig. 5.2.7. Process print that eventually collapsed.

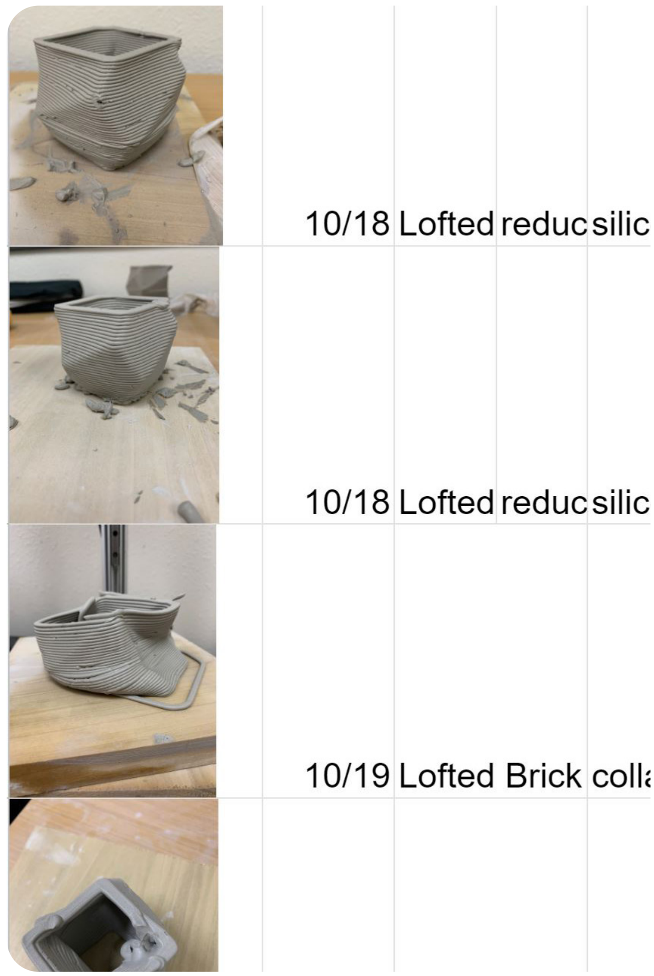


Fig. 5.2.8. Print log on Google sheet.

Throughout the 3D printing process, key variables of each printer were recorded in a Google spreadsheet including size, print speed, and design elements such as number of points, amplitude, and layer height. The live and accessible Google sheet serves as a reference for successes and failures from which to build on.

3D PRINTING PROCESS

1. Clean Cerambot of dry or residual clay.

2. Set up print bed with platform such as wood cut covered in plastic wrap, secured by tape under the board.

3. Upload gcode onto SD card either from slicer or grasshopper gcode translated to text file.

4. Retract push rod with stepper motor in hardware mode. This may take up to 50 minutes depending on the last print or retract by disassembling parts and hand turning acme rod.

5. Load clay into cartridge with straight plastic spatula compressing clay to eliminate air bubbles in clay. If sizable air bubbles are expressed in clay, it could aesthetically and/or structurally degrade the print. Reload cartridge as necessary if any bubbles are noticed.

6. Attach cartridge to stepper motor and reverse direction to push clay through hose and out to nozzle.

7. On LCD screen dial button to “Print from Media” Hit “Print”.

8. Watch print at early stages to ensure that first layers are successful.

9. Keep a broken paperclip handy to massage imperfections during the print. Using the heat gun to expedite drying time may help print.

10. When print is finished turn off stepper motor.

11. Take photograph of print and upload to Google spreadsheet log.

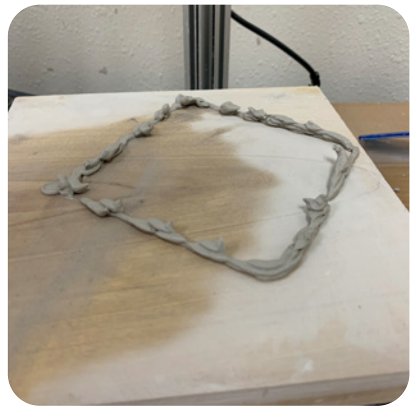
12. Let print sit on printing bed.

13. Evaluate print and document design and success of print in Google spreadsheet.

14. Label print for further documentation.

15. Clean cartridge and surrounding area using wet sponge.

1.

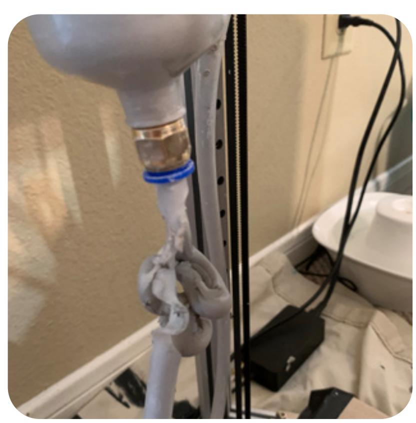


2.

3.

4.

5.



6.

Fig. 5.2.9. Troubleshooting with the Cerambot 3D clay printer.

CERAMBOT TROUBLESHOOTING

1. Air bubbles in clay explode from nozzle and degrade structure. Sometimes LCD screen goes blank and fills with white boxes (still unknown as to why).

2. 11/30/20 - Adhesion to wood bed plate inconsistent with Simplify 3D Slicer. Use of saran wrap to tape around wood bed plate will help even drying time, and prevent breaking at base, as well as encourage consistent adhesion.

3. 10/25/20 - Gear shaft compacted and shattered, preventing the push motor to move. Was able to download the gear shaft in Thingiverse and send it to the Craft Center at the University of Oregon to be 3D printed in PLA.

4. 4/9/20 - Cartridge stripped from threaded attachment, interfering with ability to print.

5. Various times when clay is too hard - silicone tube flies off hardware.

6. Various times when clay is too hard - silicone tube expands below cartridge and explodes.

9/30/20 – Ran sample tests in gcode to update Simplify3D to print. This meant that the voltage was correct, something was off with set up of the slicer.

8/28/20 – Had been using USB connection to printer from computer, but due to short cord, bought an SD card at 64 GB which was too large for the printer to read. 16 GB works fine.

8/27/20 - The current on stepper motors was set too high as print didn't seem to work. I bought a voltmeter and fine insulated screwdrivers to analyze the current and adjust it to ~435 volts.

8/9/20 - Imaginary troubleshooting – I thought hardware mode wasn't working for the pusher motor due to a dirty push rod. So, I disassembled the parts, cleaned everything well with a wire brush and greased the rod with WD-40. (It likely had been working and I wasn't able to see the movement or understand the mechanics until deconstructing it.)

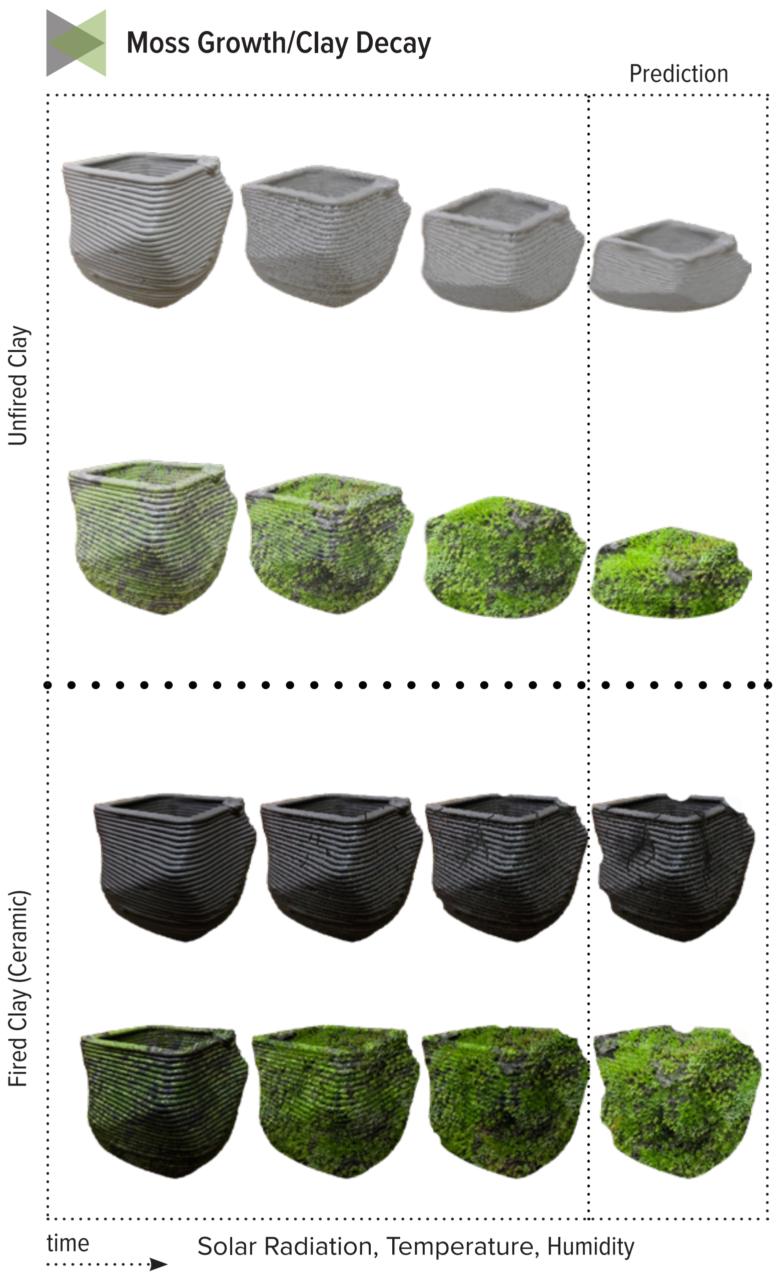


Fig. 6.0.0. Predictive diagram show moss growth on clay and ceramic substrates.

Design Goals for Experiment:

- Testing for porosity by integrating sawdust additive ratios
- Testing a combination of known and unknown mosses on all forms
- Reducing main experiment printed amount to 56
- Testing ceramic and clay substrates outdoors
- Testing on a horizontal, planar surface
- Creating a collection of variables
- Exploring the edge versus interior of cluster
- Analyzing individual forms based on variables in slope, oculus size, elevation
- Amplifying the wall thickness to create structurally sound work
- Rotating the form for structure
- Filleting the corners for successful prints
- Designing a conical form
- Interior/exterior surfaces for moss to take hold
- Grooves implied between fine grain of weave

6. EXPERIMENT

6.0 BACKGROUND

The experiment inquires how the application of fragmented mosses will grow on ceramic substrates and how designed ceramic material will respond to the application over time. This experiment is a dialogue that merges biotic and abiotic material. It seems plausible that because mosses naturally grow well on a range of substrates such as soil and concrete in the Pacific Northwest, mosses would be able to grow on designed ceramic and clay substrates. Mosses have been informally explored for their propagation, and this work aims to explore one approach in facilitating moss growth.

A significant part of the experiment tested the substrate of clay and ceramic designed through the 3D clay printer. The forms tested were conical with an interior and exterior surface. Grooves were created perfunctorily from the printer's layer deposition, and grooves were created intentionally from the design. These patterns were designed to test the response of moss growth further and evaluate the substrate's impact.

Over time, it was predicted that the clay substrates would melt with exposure to rainwater and that the ceramic substrate would chip over time. The prediction was that with a more extended period, both substrates would facilitate equal moss as seen in Figure 6.0.0.

This work was tested outdoors using a combination of identified mosses and unidentified mosses that were hand-harvested. The mosses were applied with a water solution-only to show what would happen with minimal ingredients, similar to what takes place in the natural environment, for economic efficiency to reduce costs and energy.

Four experiments were set up in total, with the main experiment set up testing fifty-six substrates in a residential area in West Eugene called the Main Experiment. The Home experiment tested three process substrates and was located on a patio in south Eugene. The third experiment was set up on the Urban Farm and tested three process substrates near a railroad at the University of Oregon. The fourth experiment was located at FMI Sales Trucks and Services and tested three process substrates in an industrial area in west Eugene. These locations were chosen for the possibility of testing moss for particulate collection to show differences in air quality.

DIDYMODON vinealis

For testing on ceramic substrate. Found growing abundantly on concrete near Lawrence Hall, University of Oregon.

COLOR of shoots discolor from brown to blackish.

TEETH of peristome is normal and pale. Almost colorless; seta 3-4mm.

SIZE Relatively small, 1-2 cm tall and grows in tufts or cushions.

IN DRIED STATE leaves contort ranging in 2.2-3.4 mm long.

CAPSULE shrunken under the mouth and strongly ribbed when dry, 1/6-2.6 mm long.

CALYPTRA are smooth or with a few hairs.

STOMATA immersed.

GROWING ON living trees, and shrubs, rarely on rock, also on artificial substrates such as aluminum or plastic window frames.

LOCATED typically on lower elevation including shrubs in urban and suburban settings.

CERATODON purpureus

For testing on clay substrate. Found growing abundantly on rock near Lawrence Hall, University of Oregon.

PLANTS open to dense tufts, turfs, or mats, green dark green, brownish green, light green or yellow-green, usually darker proximally, often dinged reddish brown or purple

SPOROPHYTE red-brown or purplish brown

CAPSULES slightly curved and inclined with a slight bulge at the base when mature, ridged when dry

IF STERILE look for short, smooth median leaf cells, the usually revolute margins, and sublet teeth at the leaf tip

WEEDY and difficult to identify

GROWING ON recently disturbed soil and after fires, as well as on many human-made substrates

LOCATED in northern hemisphere, located with mosses of similar stature and ecology, including Funaria hygrometrica, Gemmabryum, and Bryum species.

Fig. 6.0.1. All map documentation from Flora of North America Association, 2020.

SELECTED MOSSES FOR BRYOBRICK EXPERIMENT

SYNTRICHIA princeps

For testing on clay substrate. Found growing abundantly on a rooftop near Corvallis, Oregon.

LEAVES typically exhibit whorls, infoled, and weakly twisted around the stem when dry. When moist, they are concave, spatulate, 2-4mm

REPRODUCTION is only sexual.

SETA are red and 10-18mm in height.

CAPSULE is browish red, 3-4mm, and slightly curved with a distinct neck. Operculum is brown and the peristome turns red.

GROWING ON recently disturbed soil and after fires, as well as on many human-made substrates

LOCATED most commonly on west coast of North America in forest, rocky, cliff, environments and found on humus, soil, rock, and tree bark.

Fig. 6.0.2. Synrichica princeps image courtesy of Marisela de Santa Anna.

ANTITRICHIA californica

For testing on ceramic substrate. Found growing abundantly on a rooftop near Corvallis, Oregon.

PLANTS in mats, wide-spreading dark green when dry and bright green when moist.

SECONDARY STEMS grow to 10 cm and are regularly pinnate. Lateral sub branches are 1.5 cm with branchlets of 5mm.

STEM LEAVES are julaceous when dry, erect-spreading when moist, ovate-lanceolate and margins are serrulate.

PERICHATIAL LEAVES are deltoid to elongate-acuminate, basal laminal cells rectangular.

GROWING ON bark of oak trees, decorticated wood, siliceous rock, soil, humic soil, full sun or partial shade.

LOCATED on West Coast in temperate regions of North American in low to moderate elevations. Likes full sun to partial shade.

Fig. 6.0.3. Antitrcihia californica image courtesy of John Game.

Fig. 6.0.4. NE Corvallis, Oregon.

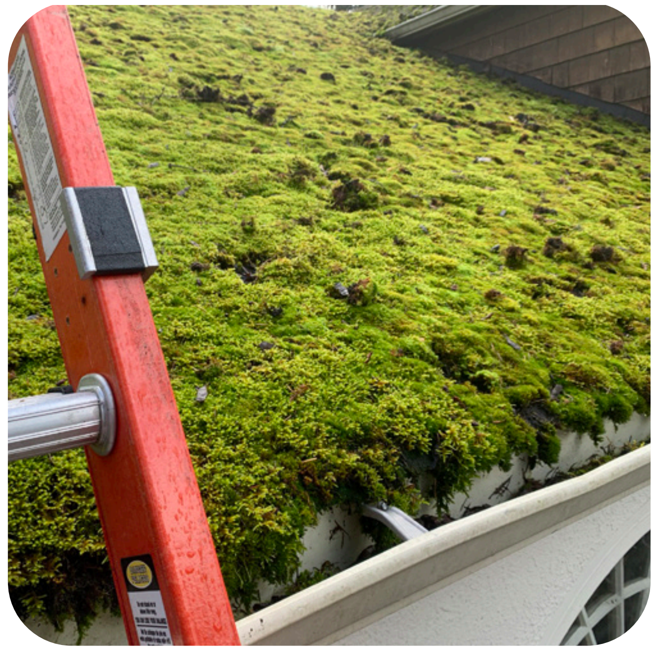


Fig. 6.0.6. Mosses collected from north and west aspects of a rooftop home.

Fig. 6.0.5. Patterson Street, Eugene, Oregon.

Fig. 6.0.7. Mosses collected from group of rocks near Patterson street.

MOSS COLLECTION SITES

The first site for moss collection was with Bruce McCune, Professor of Botany & Plant Pathology at Oregon State University in Corvallis, Oregon. With his expertise in bryology, he identified the mosses harvested from rock, roof, and soil and tested the pH of the ceramic and clay substrate. When producing the clay and moss 3D integrated forms, more moss was needed and collected near Lawrence Hall at the University of Oregon and rocks from a neighborhood in southern Eugene as seen in Figures 6.0.4-6.0.9. A range of unknown mosses were collected from the Eugene sites and were harvested from a harder substrate that demonstrated qualities similar to ceramic material.

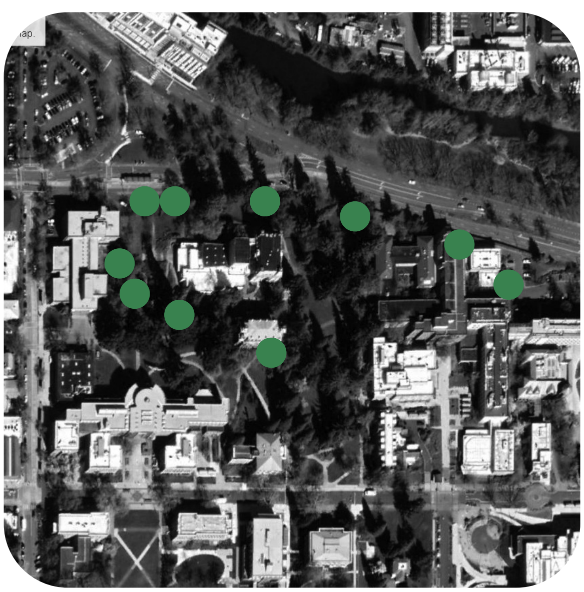


Fig. 6.0.8. Collection sites near University of Oregon, Eugene, Oregon.

Fig. 6.0.9. Collection site images.


1.


2.


3.


4.


5.


6.

Fig. 6.0.10. Moss harvesting, processing, and application methods.

MOSS PREPARATION AND APPLICATION

1. Collecting the moss involved two methods. I peeled chunks of mosses from the roof's surface in Corvallis, Oregon, and at other locations clipped only the moss tops. It was essential to collect only the green parts. The brown material, old moss, rhizoids, and other organic matter would not contribute to the propagation process.

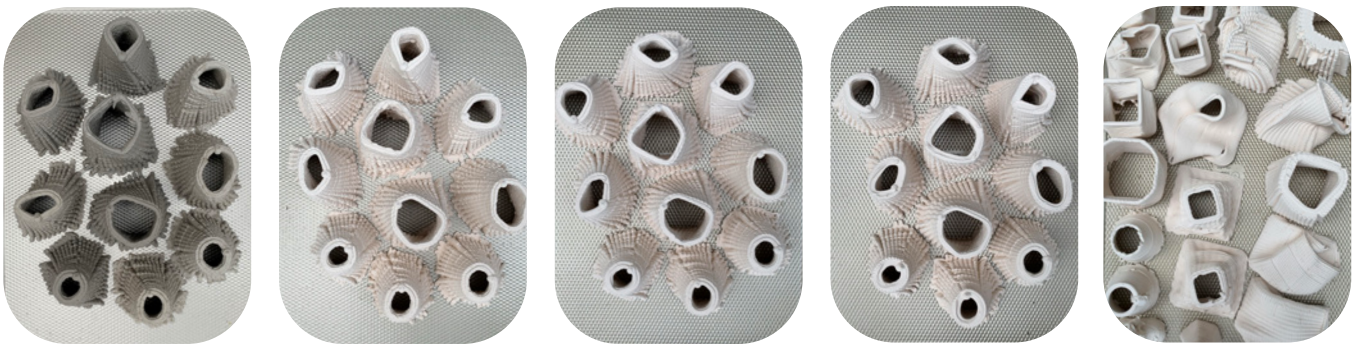
2. I chopped up all the green parts of the mosses. This propagation method is happening through fragmentation, where the mosses will reproduce asexually.

3. I collected 325 grams of mosses for the clay-only cluster and stored them in a grocery bag to allow the mosses to breathe. It was important to weigh the mosses to verify that 7% composed the clay body mix.

4. I removed the brown parts from the under green with a knife, combined this with fragmented mosses, and blended the moss into a slurry with water.

5. The mosses were applied in a wet state on the damp substrate so that the mosses would adhere with an average of 5mm thickness. This step proved challenging to distribute the mosses evenly.

6. By pressing the mosses into the ceramic body, the mosses adhered to the grooves of the internal and external surfaces of the barnacle Bryobricks.



Tray 1. Clay, 7% moss mix Tray 2. Ceramic, 10% sawdust Tray 3. Ceramic, 5% sawdust Tray 4. Ceramic Tray 5. Process Pieces

Fig. 6.1.0. Experiment set-up with different substrates.

Fig. 6.1.1. Water uptake into ceramic

Fig. 6.1.2. After heavy rainfall, pulled all experiment under eaves

Fig. 6.1.3. Detail of moss application

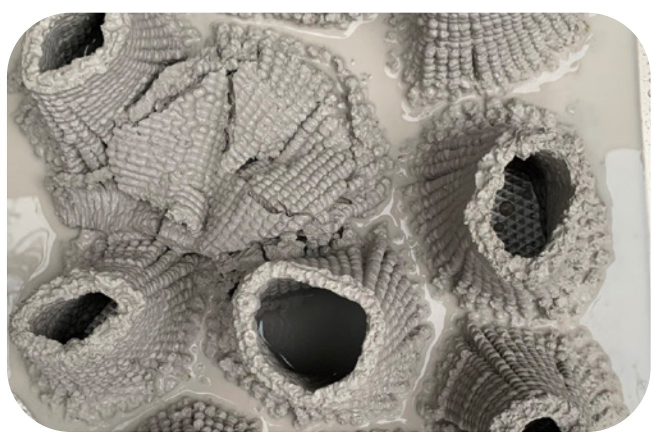


Fig. 6.1.4. Ceramic and moss cluster saturated after first rain

6.1 MAIN EXPERIMENT

The main experiment was situated on a residential deck on the second level. The purpose of the experiment was to test moss growth on varying substrates. The experiment was set up during the first week of February was consistently monitored through the beginning of May. The trays were arranged from left to right. Tray 1 was composed of clay and a 7% moss mix composition; Tray 2, ceramic with 10% sawdust burned out; Tray 3, ceramic with 5% moss burned out; Tray 4 with ceramic, and Tray 5 with ceramic process pieces.

The trays were observed through photography and writing weekly. Placing the porous barnacle substrates in the trays conveyed the water upwards to hydrate the mosses. When the experiment was first set up, it was exposed to a hard rain which removed much of the moss application. The trays were moved under the eaves to protect them during the establishment phase. The experiment was maintained through weekly hydration through misting the interfaces and refilling the trays with water. The lighting conditions were monitored by an hourly time-lapse camera operated by Raspberri Pi. A hygrometer was used to track temperature and humidity to identify potential correlations for the changes in the experiment. This is a quasi-experiment as most variables were similar, and there was not a control as seen in Figure 6.1.0.

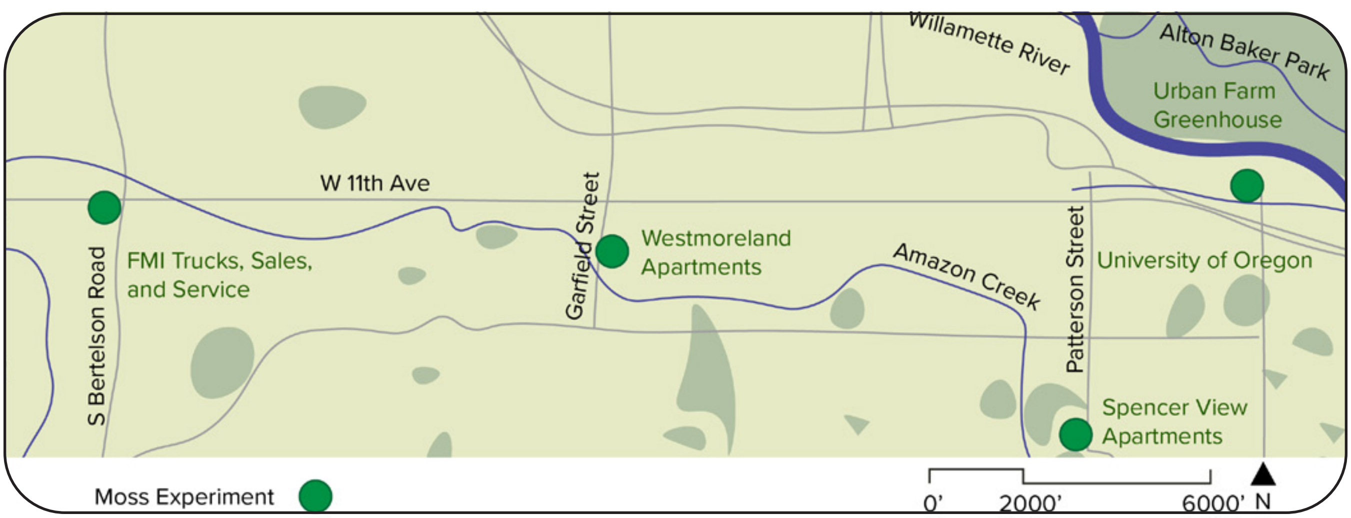


Fig. 6.1.5. Map of experiments throughout Eugene.

Fig. 6.1.6. Materiality of environment.

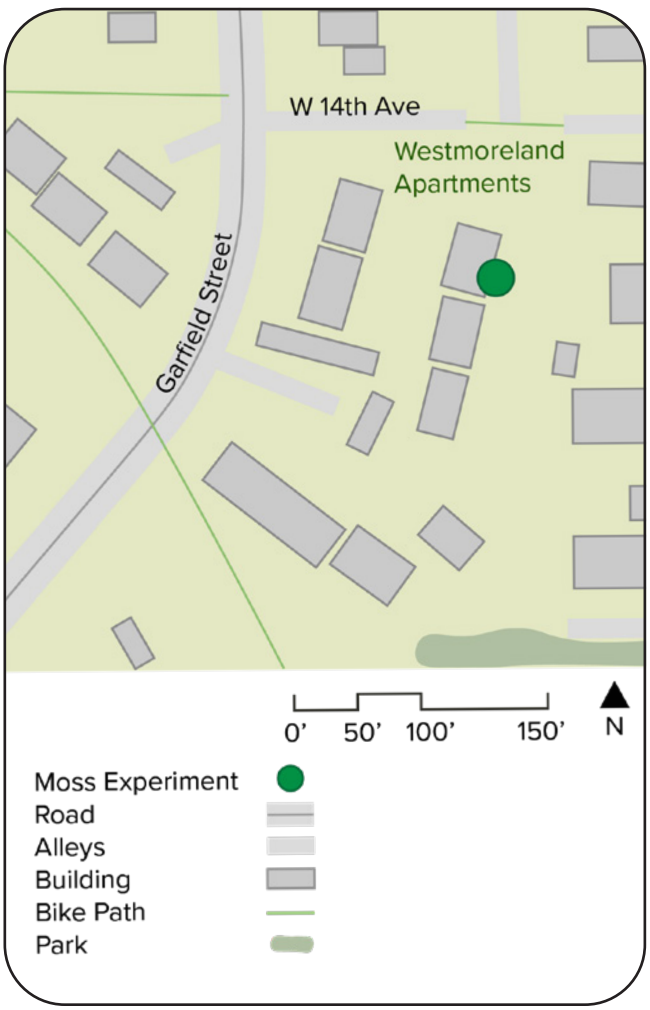


Fig. 6.1.7. Site context of experiment.

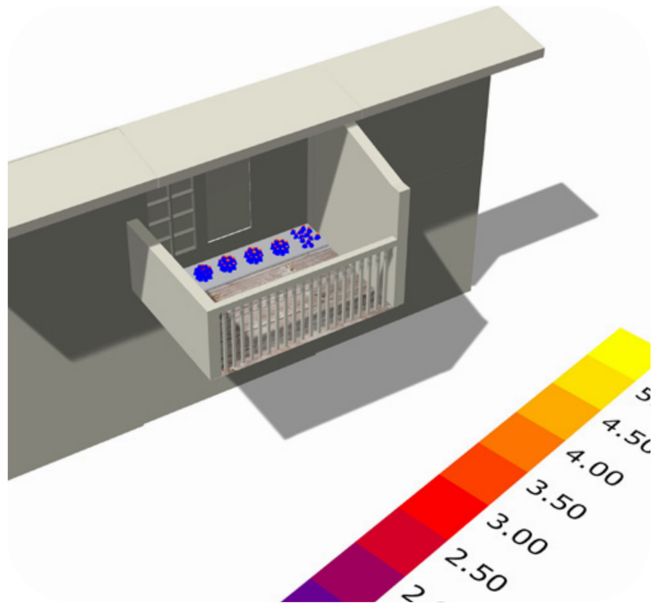


Fig. 6.1.8. Sunlight Hours Analysis (context).

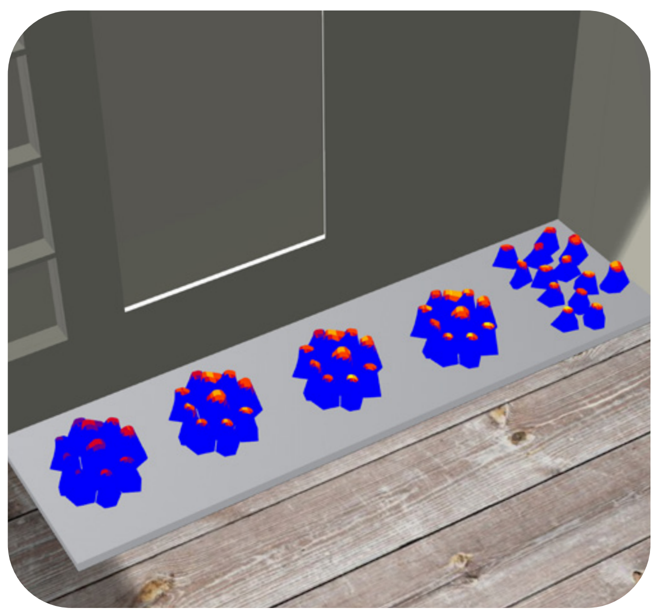


Fig. 6.1.9. Sunlight Hours Analysis (detail).

MAIN EXPERIMENT - WEST EUGENE, RESIDENTIAL DECK

The sunlight hours analysis measured exposure from 7am to 7pm on March 21. The exterior of the interfaces showed that they receive less than .5 hours of daylight, and the interior area near the rim received 5-2.5 or 1.5 hours of sunlight. It can be assumed that these hours may be transposed. The solar radiation analysis on the exterior of the interfaces showed that they receive 4.05 kWH/m2 radiation, and the interior area near the rim received 12.16 to 20 kWH/m2 radiation. It can be assumed that these hours may be transposed. At 2pm on 3/15, midway through the experiment, the shadow analysis shows that the experiment was in a shaded environment.

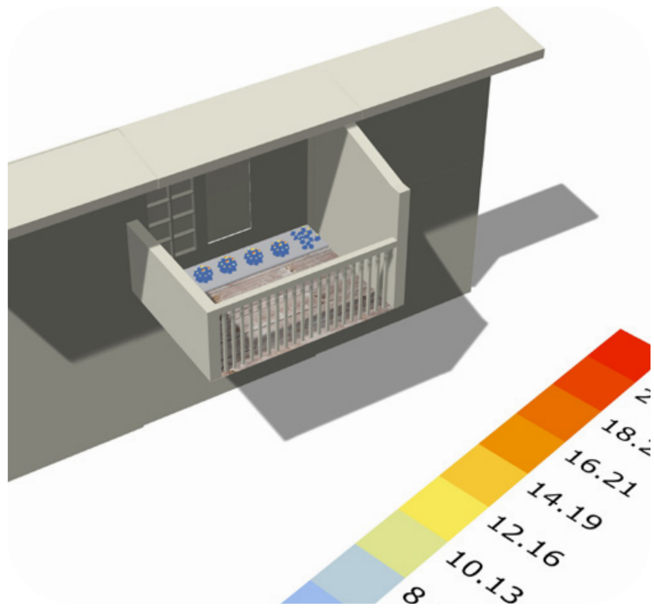


Fig. 6.1.11. Solar Radiation Analysis (context).

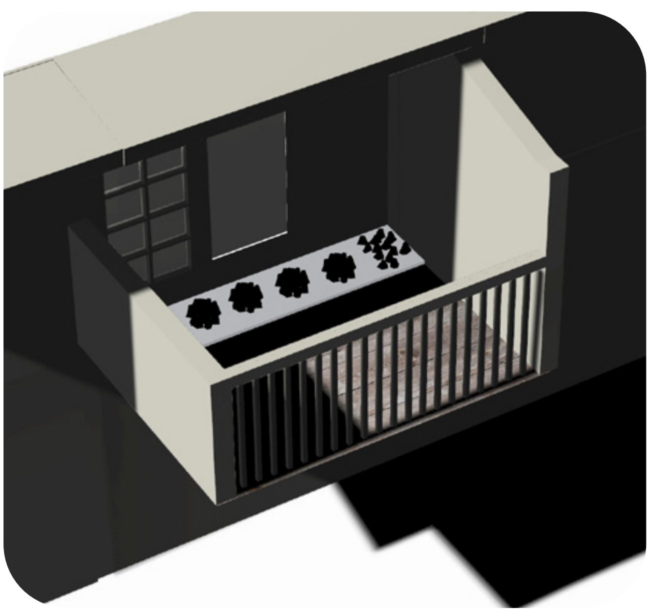


Fig. 6.1.10. Shadow Study at 2pm on 3/15/21.

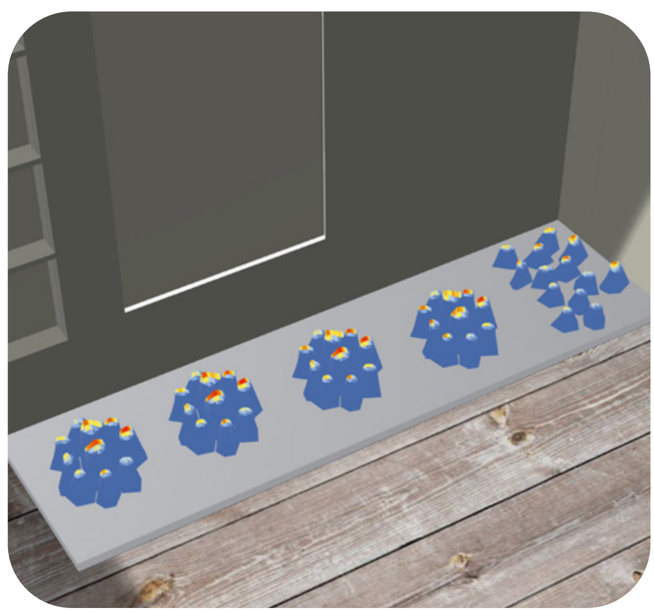
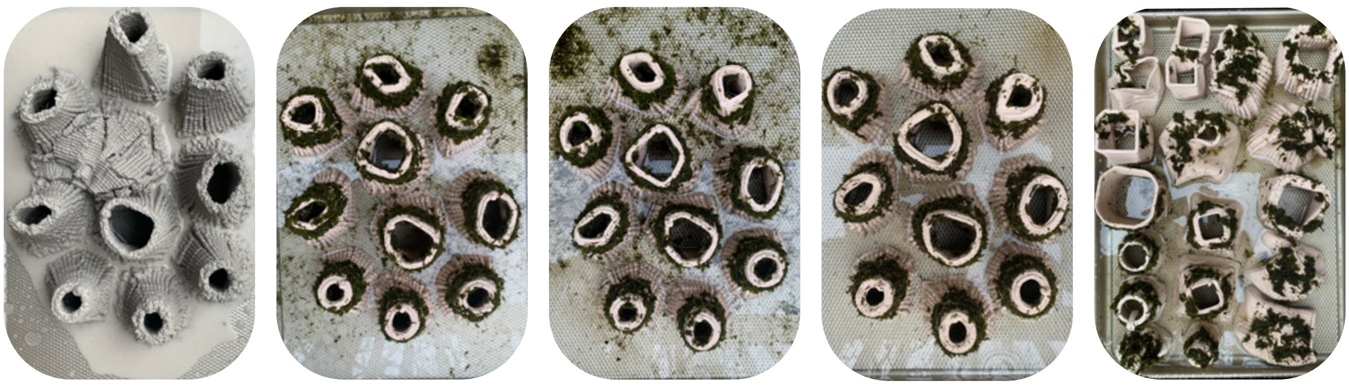


Fig. 6.1.12. Solar Radiation Analysis (detail).

Clay, 7% moss | Ceramic, 10% sawdust | Ceramic, 5% sawdust | 4. Ceramic | Process Pieces



Week 1 - February 7, 2021

Week 2 - February 14, 2021

Week 3 - February 21, 2021

Fig. 6.1.13. Documentation of weeks 1-3 of Main experiment.

Clay,
7% moss

Ceramic,
10% sawdust

Ceramic,
5% sawdust

4. Ceramic

Process Pieces

Week 4 - February 28, 2021

Week 5 - March 8, 2021

Week 6 - March 14, 2021

Fig. 6.1.14. Documentation of weeks 4-6 of Main experiment.

Clay, 7% moss | Ceramic, 10% sawdust | Ceramic, 5% sawdust | 4. Ceramic | Process Pieces

Week 7 - March 21, 2021

Week 8 - March 29, 2021

Week 9 - April 4, 2021

Fig. 6.1.15. Documentation of weeks 7-9 of Main experiment.

Clay, 7% moss | Ceramic, 10% sawdust | Ceramic, 5% sawdust | 4. Ceramic | Process Pieces

Week 10 - April 11, 2021

Week 11 - April 18, 2021

Week 12 - April 25, 2021

Fig. 6.1.16. Documentation of weeks 10-12 of Main experiment.

Fig. 6.1.17. Week Two - February 14, 2021.

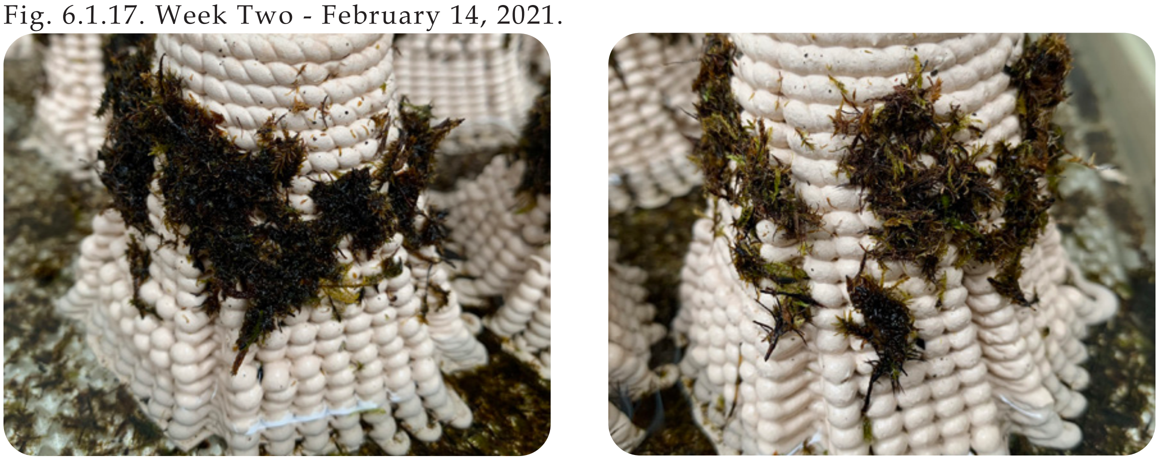


Fig. 6.1.18. Week Three - February 21, 2021.

Fig. 6.1.19. Week Four - February 28, 2021.

MAIN EXPERIMENT FIELD NOTES

Week One - 2/7/21

After placing the trays out with mosses applied, it rained hard the first night, drawing the mosses down to the water in the trays. I took the fallen moss fragments and reapplied them to substrate, then moving the trays under the eaves where there would be protected from the falling rain.

Week Two - 2/14/21

Mosses appear darker in color and continue to fall from substrate. The clay pieces seems to be drying up and showing cracking at the bottom of the pieces.

Week Three - 2/21/21

Tray 1 is completely dry and there is no sign of moss showing. I refilled the tray. Lots of moss has fallen into the trays of water. The moss is wet to the touch and there are some pieces that show green. I wonder if the green moss is part of larger segments of moss that has been alive since fragmentation. The water seems clean and possibly appears cleaner than week two. The mosses are finding their way into some of the grooved spaces. The mosses are hanging around the midsection and peeling away from the ceramic slightly.

Week Four - 2/28/21

Salt crystals are growing at the tops of the ceramic substrate and seem to be growing more on the taller substrate pieces. Note that most of the mosses have fallen from the process pieces that contain less texture and groove. The mosses that are sticking are in the central part of the ceramic substrate pieces.


Fig. 6.1.20. Week Five - March 8, 2021.


Fig. 6.1.21. Week Six - March 14, 2021.


Fig. 6.1.22. Week Seven - March 21, 2021.

Week Five - 3/8/21

The trays of water have evaporated, so the hydration to the ceramic substrate has caused the moss to dry up as well. Some of the mosses remain in tact while pulling away from the ceramic forms. In certain deeper grooves, it seems that a dark green material is establishing. White crystals seem to be growing on the taller forms. Small pieces of mosses seem to adhere to the ceramic forms. Towards the base of the ceramic substrate, thed don’t seem to be latching on as well.

Week Six - 3/14/21

A spiderweb is found growing along the top of ceramic piece #5 in tray four. The crystals seem to be growing even along the tips of the mosses. The mosses appear lighter in color and dried out. On ceramic piece #1 in tray 2, mosses are latching on to the irregular grooves along the central part of the piece. I have started misting the ceramic pieces occasionally with water vapor to assist with hydration as they are not receiving water flow movement from the rain.

Week Seven - 3/21/21

There seems to be a darker pigmentation near the rims of the ceramic substrates. Salt crystals are growing more intensely and in greater sized chunks along the rim. Some of the moss is clinging to the interior of the pieces, but less is clinging on there as opposed to the exterior.

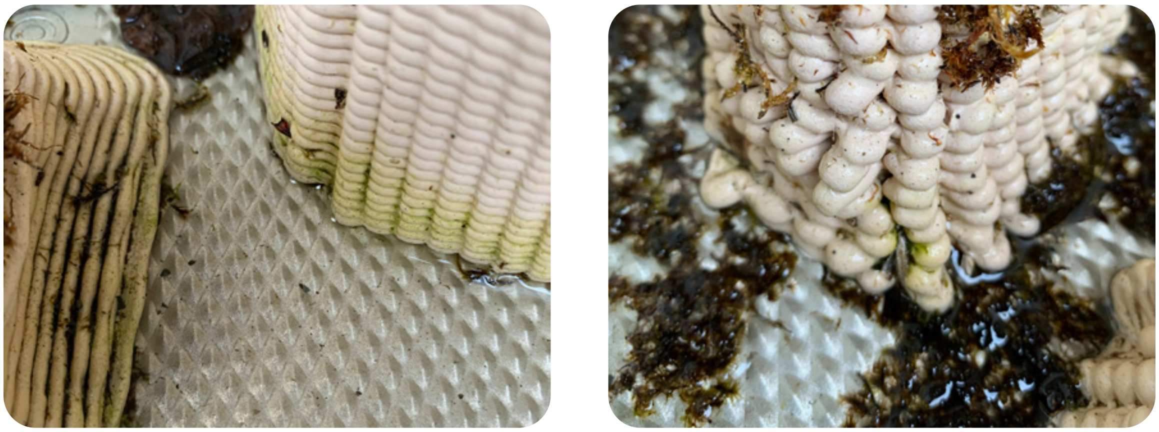


Fig. 6.1.23. Week Nine - April 5, 2021.

Fig. 6.1.24. Week Ten - April 12, 2021.

Fig. 6.1.25. Week Eleven - April 19, 2021.

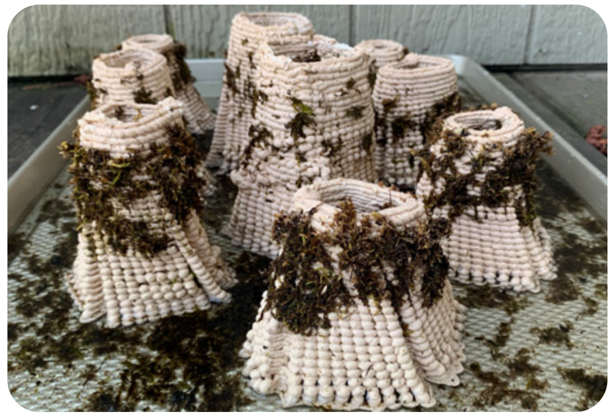
Week Eight - 3/29/21
The mosses have dried out, so I refilled they trays with water. Some of the mosses are holding onto the grooves. There is more salt accumulation around the tops. A spider web has expanded to other process pieces in tray 2. I have been sporadically misting the pieces. It seems that discoloration is appearing on the process pieces.

Week Nine - 4/5/21
A light-colored substance seems to be showing up near the bottoms of the ceramic substrate especially near the process pieces. This is surprising because there does not seem to be fragments of mosses attached near these areas. I wonder if something is transporting the spores to these areas or if the water seems to transport the spores?

Week Ten - 4/12/21
The tops of the tallest pieces are not showing signs of moss growth and are quite fragile to the touch. This is because evaporation from the ceramic substrate exceeds the runoff, so the salt is not able to move. The green coating along the bases is most prominent on the process pieces that receive the most shade. The bases from other parts of the experiment are showing a greenish hue. The dried moss pieces are light in color and are slightly secured to the substrate.

Week Eleven - 4/19/21
In tray 2 of ceramic with 10% sawdust burnout, barnacles 8 and 9 are showing green. In tray 3, barnacles 8 and 10 are showing green on the north side and inside. All have darker hue at the base. There is significant chipping at the tops of the tallest barnacles due to the salt crystals. In tray 4, all but barnacles 4 and 5 are showing green at the base. Barnacle 9 is the exhibits the most green on the Northwest side. In tray 5 of the process pieces, all show signs of protonema growth at the base. When misting the experiment, the upper mosses become unattached.

North-facing



West-facing

South-facing

East-facing

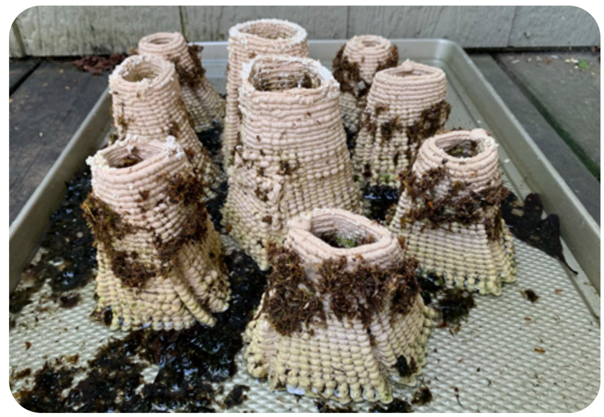
March 12, 2021, Week 5

It seems that there was not a significant difference between growth of four aspect.

Fig. 6.1.26. Cardinal aspect visual analysis mid-experiment.

MIDWAY AND FINAL ANALYSIS: ASPECT

North-facing



West-facing

South-facing

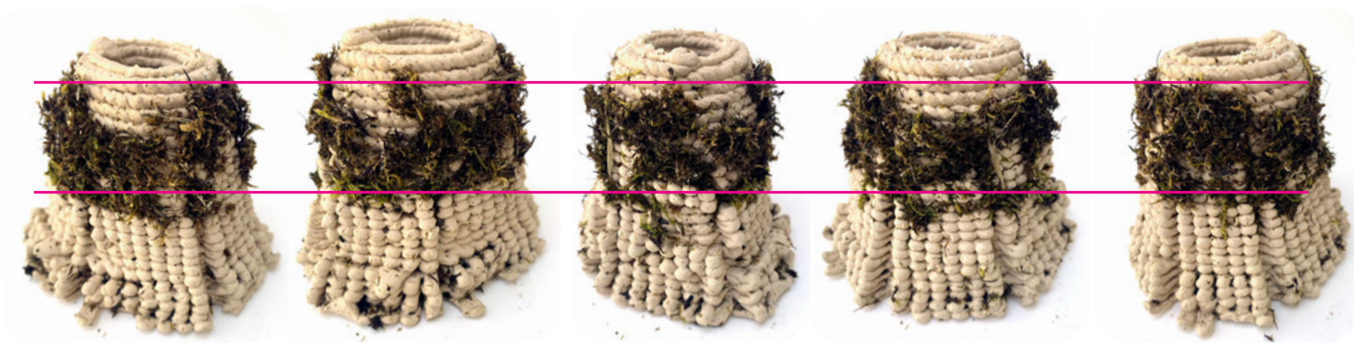
East-facing

April 29, 2021, Week 12

The north-facing interfaces showed the highest concentration of protonema growth, whereas on the south-facing side the green was more towards the bases. The west-facing side held more of the original moss application. All forms showed signs of protonema growth at the base.

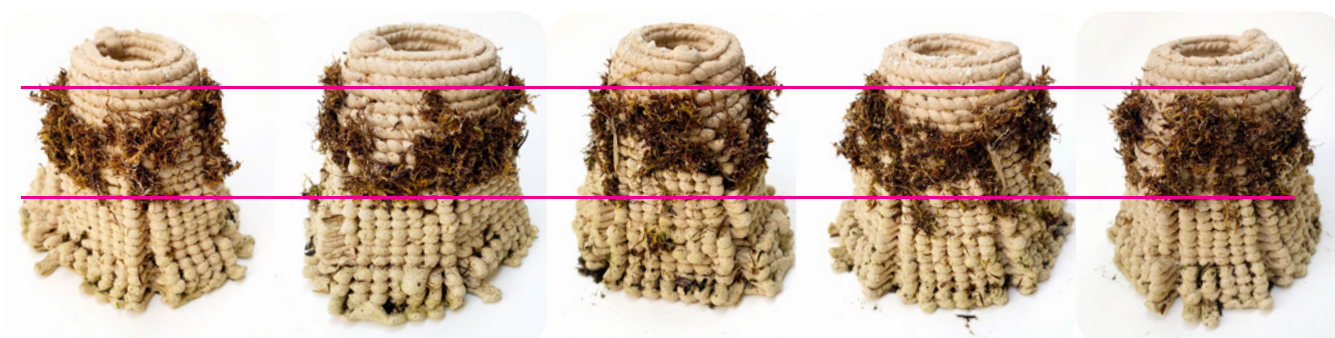
Fig. 6.1.27. Cardinal aspect visual analysis at end of experiment.

March 12, 2021, Week 5



Barnacle interface #5 of the most porous group showed moss retention (possibility for growth) along mid-section of amplification ranging from 4-8 mm. Amplification was likely too little near the rim and too great near the base. There was also the possibility that the water in the trays disturbed or over saturated the ceramic at the base.

April 29, 2021, Week 12

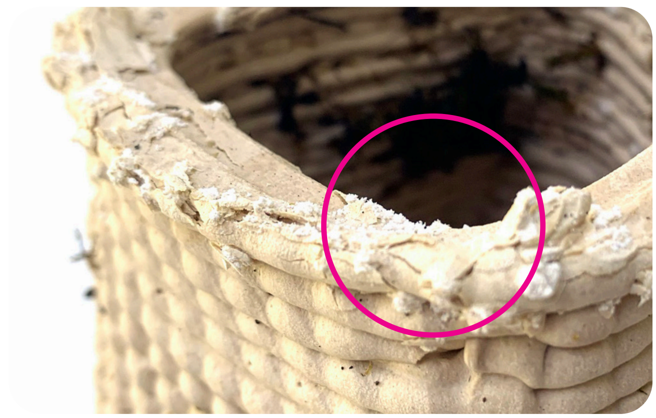


The moss held on particularly well on barnacle interface #5. Where the fragmented moss fell near the base, the moss settled in and grew into protonema. The white tips on the applied mosses seemed to fade away with time.

Fig. 6.1.28.Texture visual analysis of 72 degrees rotation at midway and at end of experiment.

MIDWAY AND FINAL ANALYSIS: TEXTURE AND SALT

March 12, 2021, Week 5



Barnacle Interface #1 and #5 of ceramic-only substrate showed salt crystal build-up near the lip of the interface. Salt crystals accumulated at greater levels of interfaces greater height.

April 29, 2021, Week 12

The salt crystals proved to be non-problematic to barnacle interface #5, however, the crystals continued to build and chip away at the rim of barnacle interface #1.

Fig. 6.1.29. Salt crystal visual analysis at midway and at end of experiment.

March 12, 2021, Week 5

Barnacle Interface #2 from most porous group. Moss accumulation was low where it was wet near the the base, higher in the central area, and least accumulating at the rim where was drier and most exposed to the elements.

Fig. 6.1.30. Hydration and height visual analysis at midway of experiment.

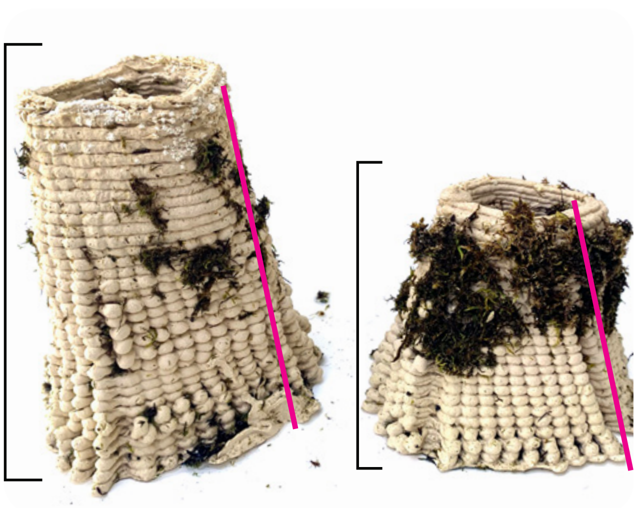
MIDWAY AND FINAL ANALYSIS: HYDRATION + HEIGHT

April 29, 2021, Week 12

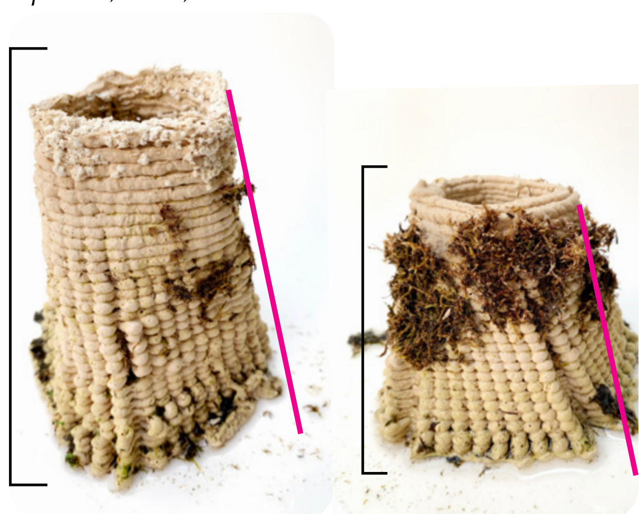
Barnacle Interface #2 from most porous group. Moss growth and cotyledon showed establishment where it was wet near the base. In the mid-section, the moss had moved deeper into the grooves and speckles of green were apparent. The rim had accumulated a significant collection of salt crystals and were detrimental to the structural integrity of the interfaces.

Fig. 6.1.31. Hydration and height visual analysis at end of experiment.

March 12, 2021, Week 5



April 29, 2021, Week 12



On Barnacle Interface #1 of most porous group, less moss remained in comparison to Barnacle Interface #9 likely due to the response in slope. Less height is okay for this design.

The moss attachment did not significantly change with these pieces. Again, the height of barnacle interface #1 facilitated salt crystal accumulation and there was less moss attachment in comparison to the shorter, less sloped #9.

Fig. 6.1.32. Height and slope visual analysis at midway and at end of experiment.

MIDWAY AND FINAL ANALYSIS: SLOPE, HEIGHT, INTERIOR

March 12, 2021, Week 5

On Barnacle Interface #9 of most porous group, moss clung to the interior space. Protection from elements was important during the establishment phase.

April 29, 2021, Week 12

On Barnacle Interface #9, within the interior, protonema growth was showing. A bit of salt accumulation occurred as well and could be reduced with more increased periods of misting.

Fig. 6.1.33. Interior analysis at midway and at end of experiment.

Fig. 6.1.34. Protonema shown growing best on barnacle #9 of ceramic-only.

MACROPHOTOGRAPHY ON IPHONE FROM MAY 14TH, 2021

Fig. 6.1.35. All trays had small cotyledons growing near the base.

Fig. 6.1.36. From the process group, a gradient of protonema covers the shaded face of the ceramic.

Fig. 6.1.37. Protonema growing along the interior of the barnacle on interface #10.

Fig. 6.1.38. 47X amplification of filamentous material on ceramic-only barnacle #9.

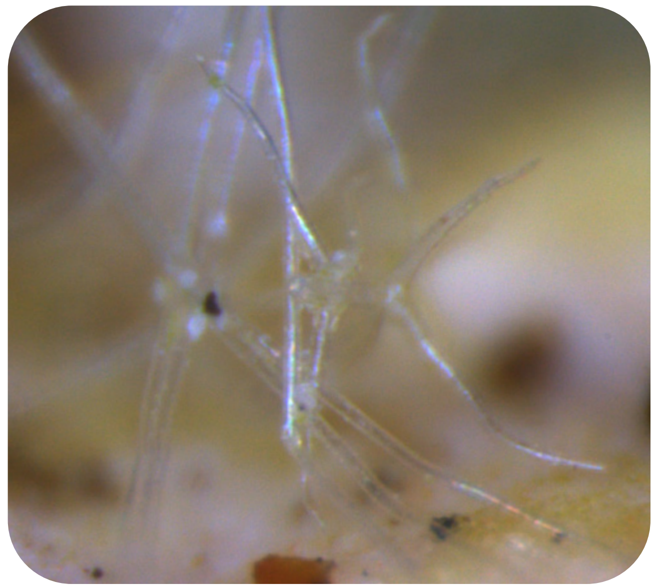


Fig. 6.1.39. 82X amplification of filamentous material on ceramic-only barnacle #9.

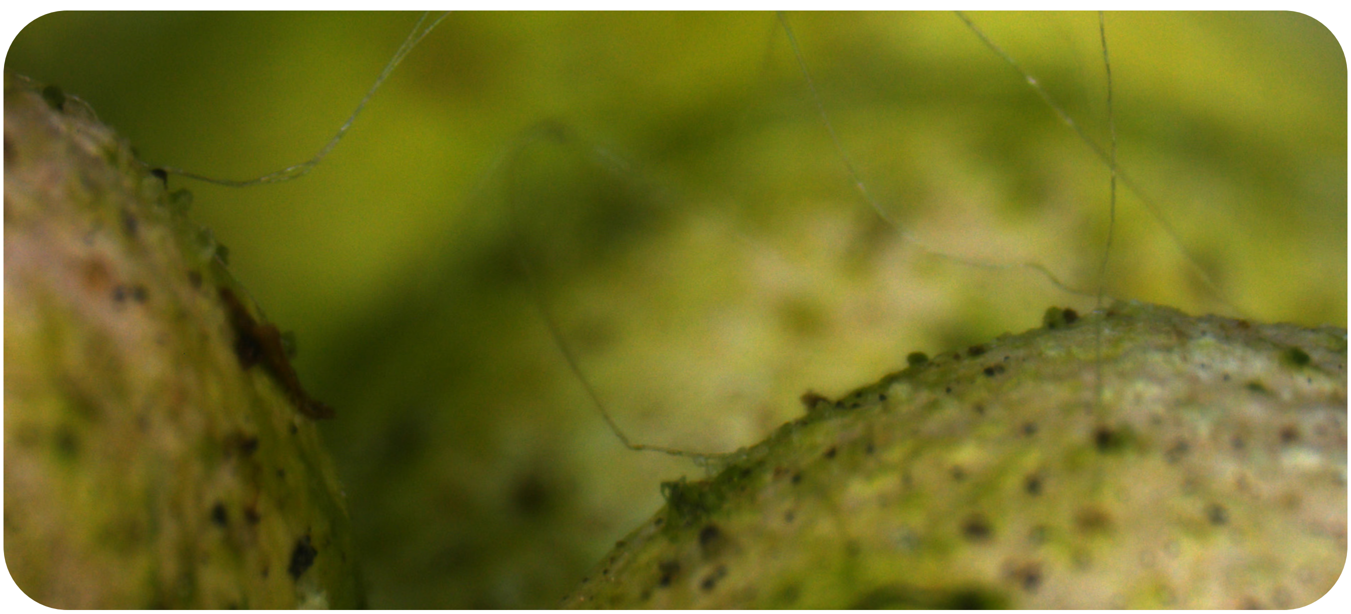


Fig. 6.1.40. 16X amplification of unknown filamentous material on ceramic-only barnacle #9.

IMAGES PRODUCED WITH ZEISS STEREOSCOPE USING ZEN2

Observing mosses with my eyes, iPhone camera, and macro photography attachment allowed me to document conditions at certain scales over time. To understand the development on the ceramic substrate and identify the mosses when the gametophytes establish, it is crucial to observe them under the microscope. A disclaimer for the results and effectively this Master's Project is that I am calling the green that occurs across all experiments protonema. Protonema is the first filamentous stage of moss growth that resembles algae. For verification, the green needs to be identified under the microscope and is outside of my capacity to confirm. At CAMCOR, at the University of Oregon, with Kurt Langworthy's accommodation, I observed surprising forms under the microscope at amplification ranging from 20X to 100X as seen in Figures 6.1.38. to Figures 6.1.44. The images included here are of the ceramic-only substrate of barnacle #9 that showed the greatest protonema growth near the base. The images on the left show unknown filamentous material. The image to the right shows rhizoids likely developing from the moss spores. On the following page, Fig. 6.1.42. shows protonema growth at 82X amplification.

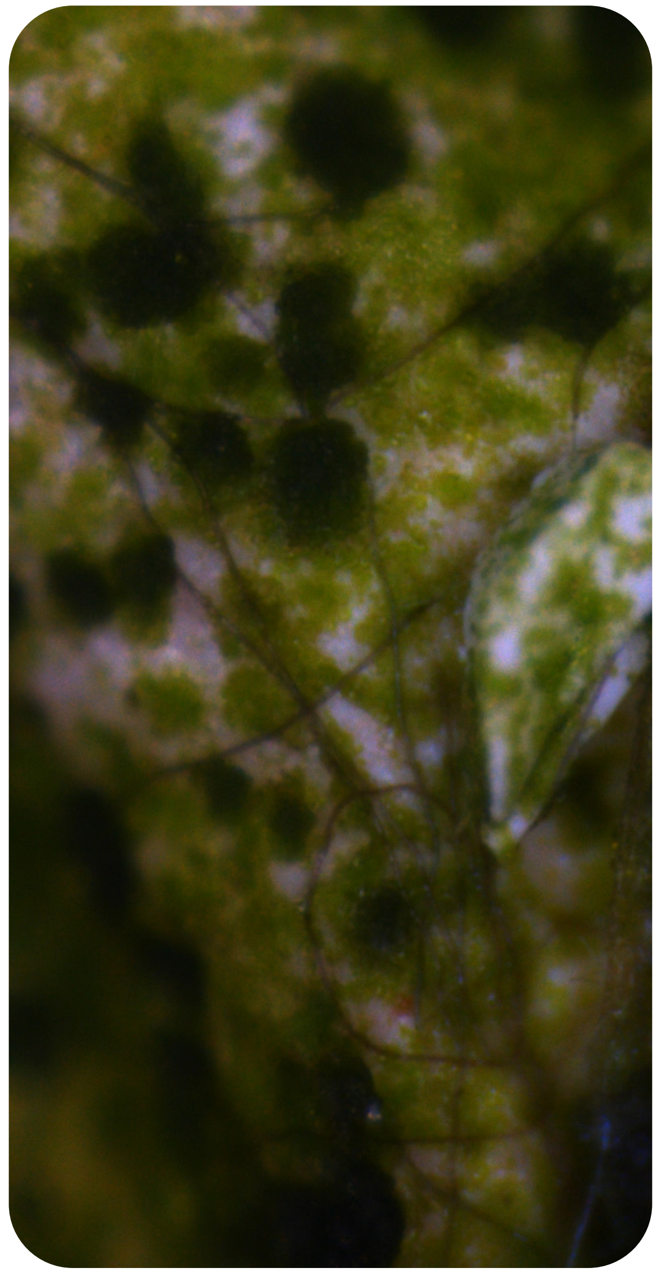


Fig. 6.1.41. 50X amplification of moss spores and rhizoid development on ceramic-only, barnacle #9.

Fig. 6.1.42. 82 X amplification showing speculative moss protonema filament growth.

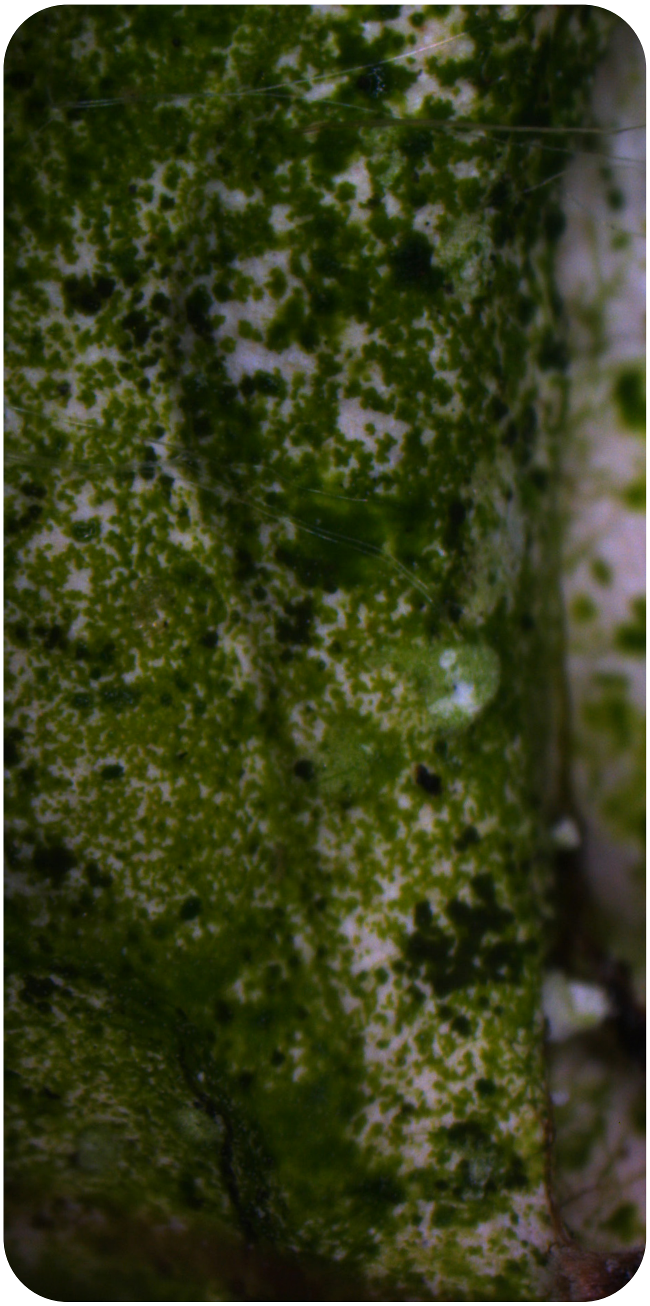


Fig. 6.1.43. 20X amplification showing development on ceramic-only barnacle #9.

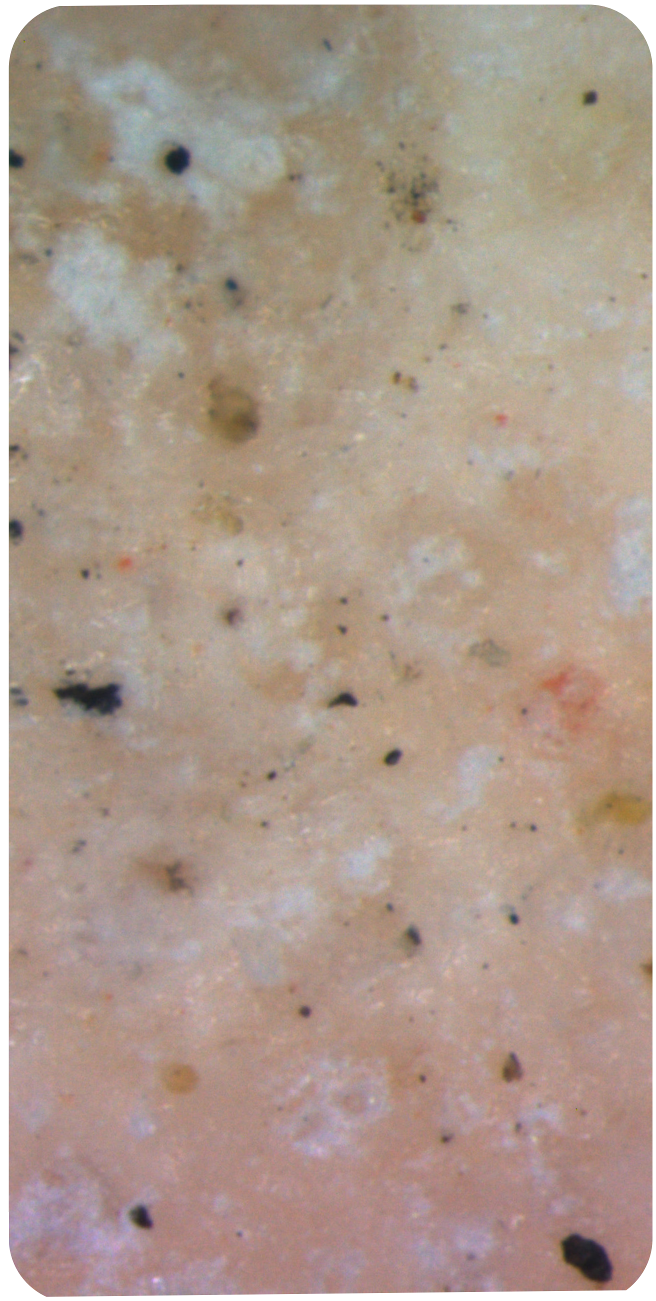


Fig. 6.1.44. 82X amplification showing salt development on ceramic-only barnacle #9.


3/
mic
awdust
1.
2.
3.
4.
5.
4/
mic
3/
mic
awdust
2/
mic
sawdust
1/
7%
s mix
Too damaged to transport for photo.
Too damaged to transport for photo.

FINAL SHOTS OF THE BARNACLE INTERFACES

Fig. 6.1.45. Moss results for each barnacle. See page 128 for pre-experiment substrates.

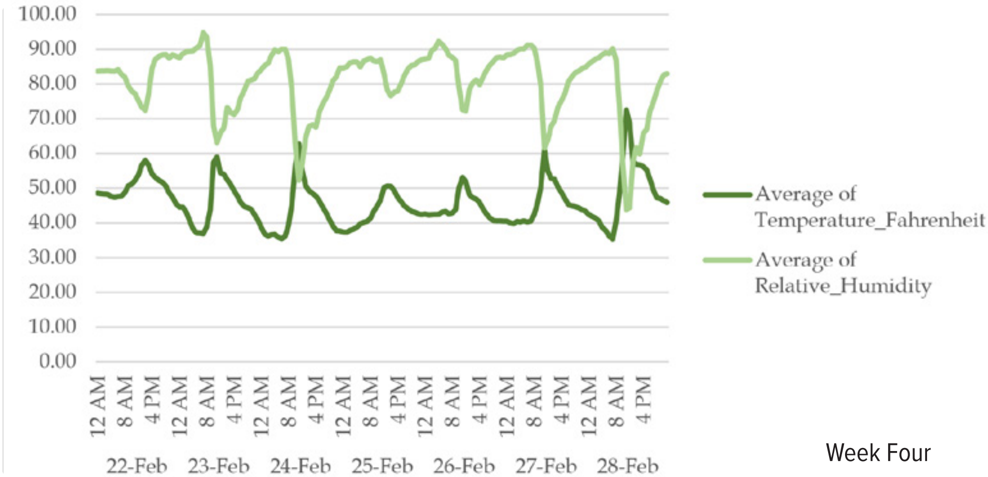
Fig. 6.1.46. Process pieces shown in print order.

FINAL SHOTS OF THE PROCESS PIECES

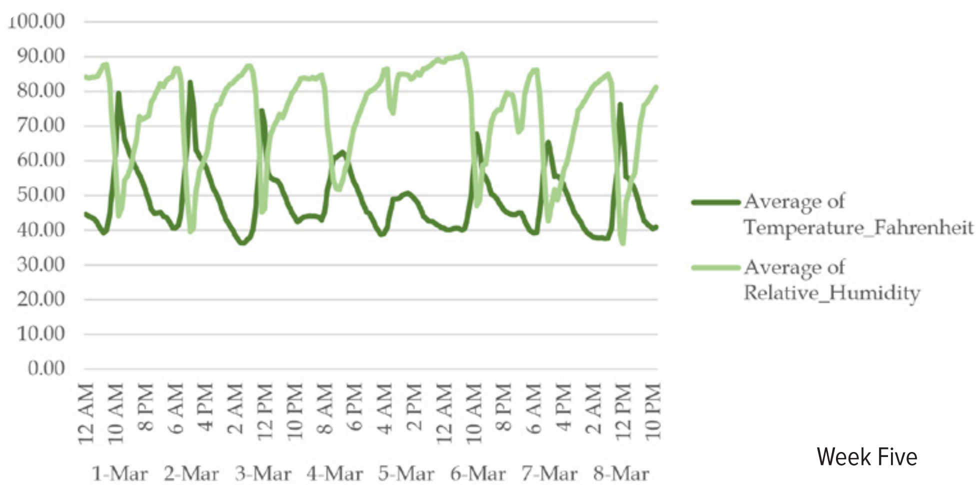
The process pieces were located near the northwest corner space and received more shade. The increased shade was created due to the placement of a large bag on the patio. Even though the structures on these pieces lost the most applied moss growth, they showed significant protonema growth at the base as seen in Figure 6.1.46. With time, it would be interesting to see how the protonema will evolve on the process pieces compared to the more grooved barnacle interfaces.

The clay and moss combined substrate on the right show no moss growth at all as seen in Figure 6.1.47. The substrate is bone dry and holds no moisture. The lack of development was likely due to the entrapment of the moss and halted the possibility for photosynthesis.

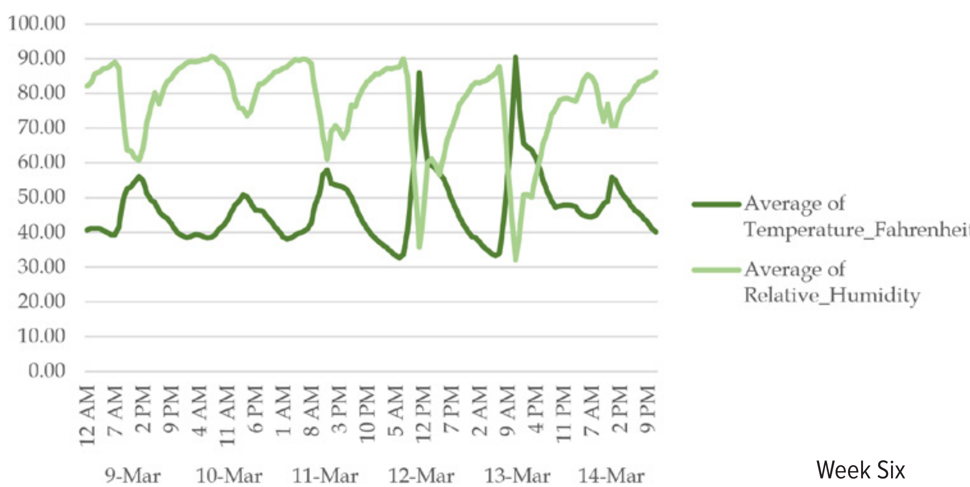
Fig. 6.1.47. Clay and moss substrate showed no moss growth.



Week Four



Week Five



Week Six

ENVIRONMENTAL CONDITIONS

A Govee hygrometer was used at the location of the Main experiment to track the percentage relative humidity and temperature in Fahrenheit as seen in Figure 6.1.48. It was essential to track environmental conditions as the moisture and temperature had an impactontheexperiment. Environmental conditions were critical, for there was little maintenance on the FMI Home experiments. It can be assumed that with greater relative humidity, the experiment would have greater success. It would have been ideal to start the experiment earlier in the season to maximize higher relative humidity conditions. These graphs show weeks four through week nine because this was when the Govee hygrometer functioned adequately. Humidity and temperature are inversely related to humidity typically peaking in the early morning hours and temperature peaking mid pm hours. Higher temperature patterns occurred earlier in the day during week four and by week eight occurred mid-day. Humidity generally decreased from the span of week four to nine, dropping by 20%.

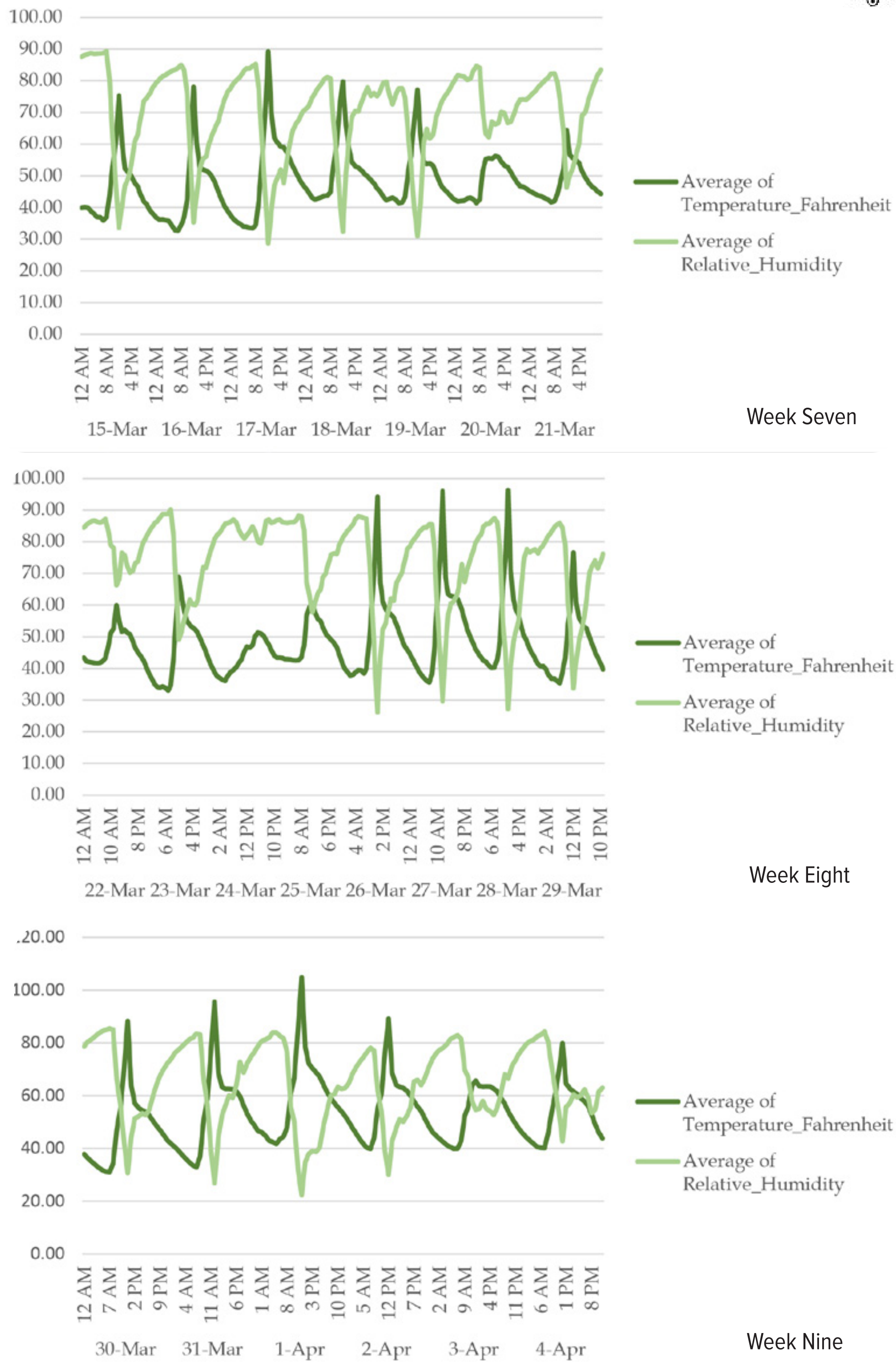


Fig. 6.1.48. Hygrometer and temperature data recorded from weeks four through nine at main experiment site.

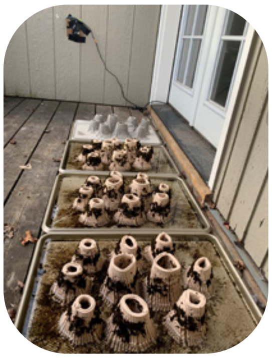
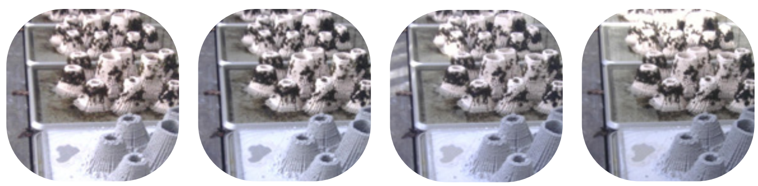


Fig. 6.1.49. Vantage point of time lapse from Main experiment.

Fig. 6.1.50. Raspberry Pi Camera Lens that captured time lapse images.

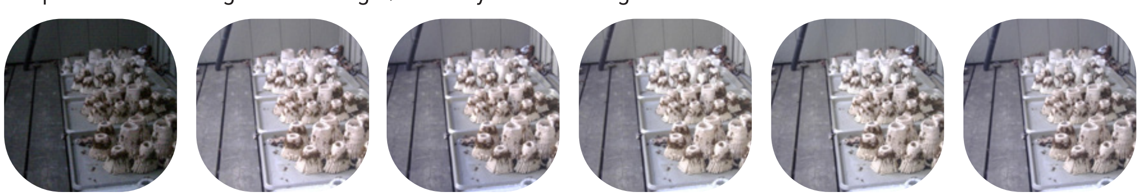


9am 10am 11am 12pm

February 8, 2021
Temperature: 39.8 degrees F average | Humidity: 81.9% average

7am 8am 9am 10am 11am 12pm

March 8, 2021
Temperature: 41.92 degrees F average | Humidity: 81.2% average



7am 8am 9am 10am 11am 12pm

April 8, 2021
Temperature: 46.29 degrees F average | Humidity: 69.0% average

MAIN EXPERIMENT, HOURLY, DAILY TIME LAPSE

From February 8th to April 25th, 2021, a Raspberri Pi camera captured images of the experiment on an hourly basis from an axon perspective. This documentation shows the specific lighting conditions across the hours of the day with the changes in solar exposure, aspect, and weather. This documentation serves as a general snapshot across all the trays. Due to the camera's make-shift attachment to the wall, the lens shifted towards the end of the experiment, compromising a consistent recording. At the end of the experiment, the photos were compiled to make a time-lapse video to experience specific changes in lighting conditions over time as seen in Figure 6.1.51.

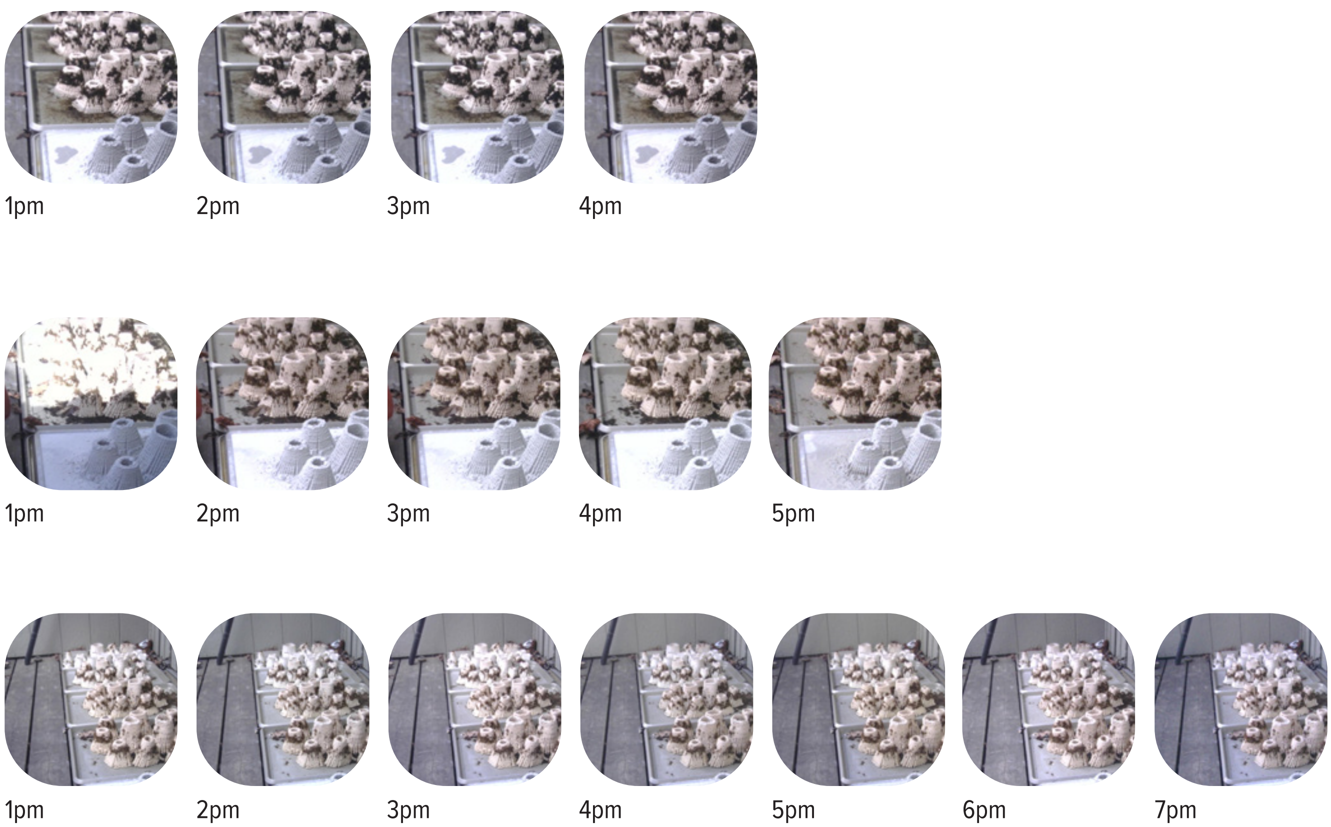


Fig. 6.1.51. Images taken during each month of experiment on an hourly basis showing change in length of days.

Fig. 6.2.0. Materiality of environment.

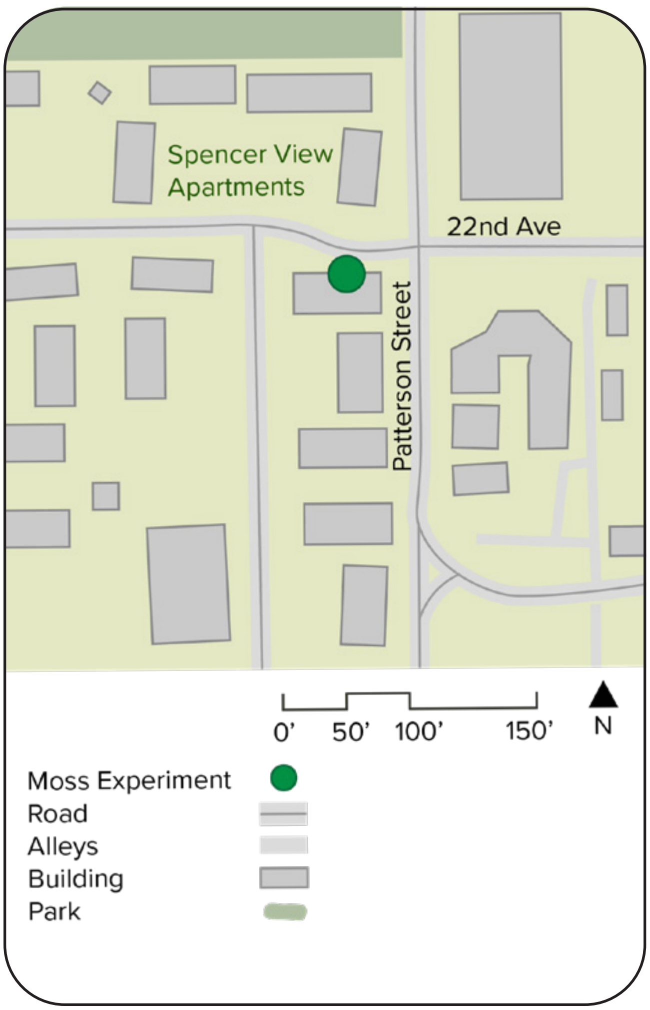


Fig. 6.2.1. Site context of experiment.

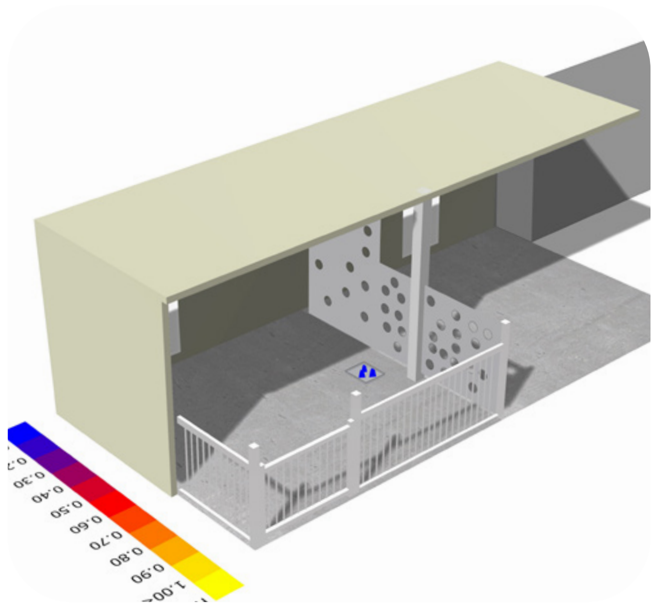


Fig. 6.2.2. Sunlight Hours Analysis (context).

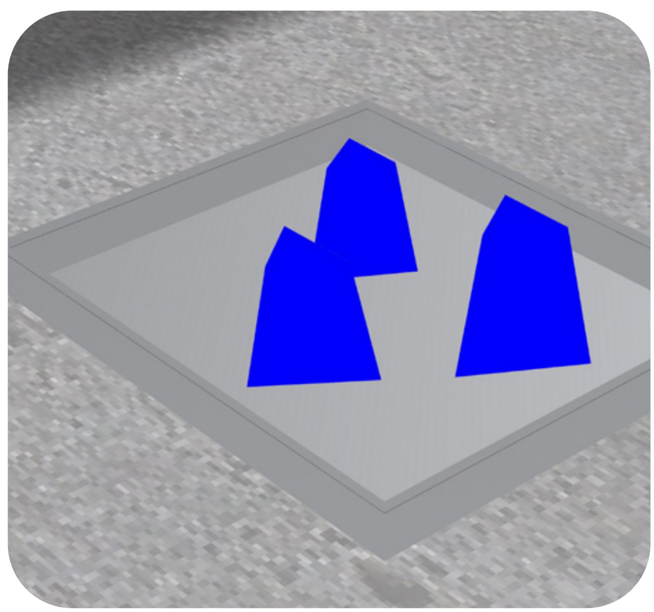


Fig. 6.2.3. Sunlight Hours Analysis (detail).

6.2 HOME, PATTERSON STREET

The sunlight hours analysis measured exposure from 7am to 7pm on March 21. The analysis showed that all interfaces receive less than one daylight hour from 7am to 7pm on March 21. The solar radiation analysis on the east-facing side of the interfaces received more than 5.19 kWh/m2 radiation to 2.59 kWh/m2 radiation. The upper-most part of the interface showed equal radiation of 3.63 kWh/m2. At 2pm on 3/15, midway through the experiment, the shadow analysis showed that the experiment was in a shaded environment.

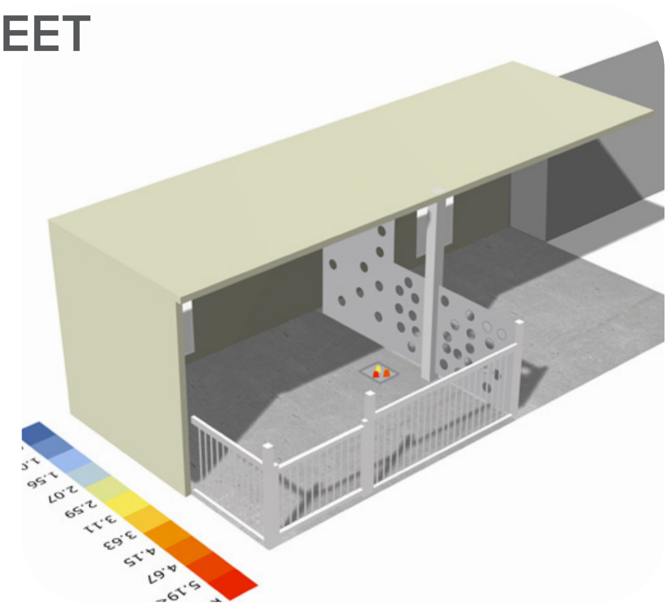


Fig. 6.2.5. Solar Radiation Analysis (context).

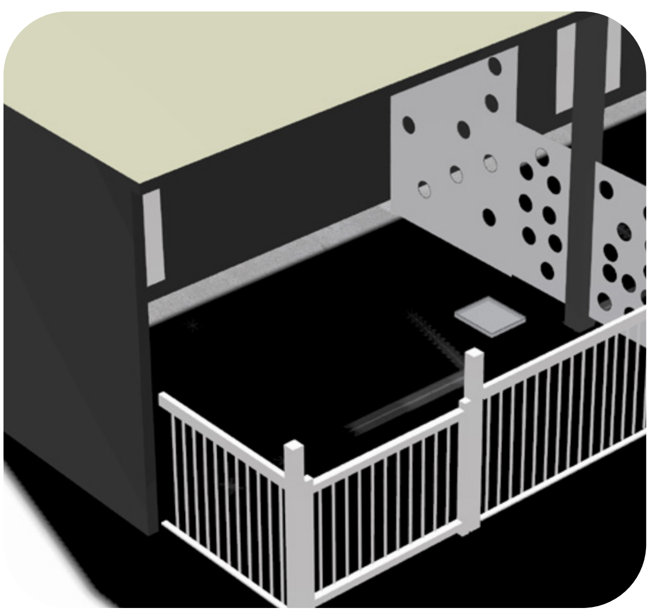


Fig. 6.2.4. Shadow Study at 2pm on 3/15/21.

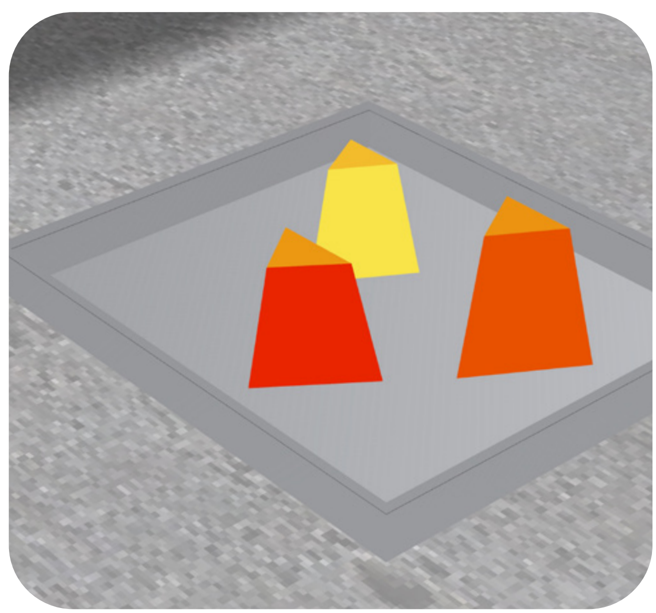


Fig. 6.2.6. Solar Radiation Analysis (detail).

Fig. 6.2.7. Week 1 - February 6, 2021.

Fig. 6.2.8. Week 3 - February 21, 2021.

Fig. 6.2.9. Week 4 - March 8, 2021.

Fig. 6.2.10. Week 10 - April 11, 2021.

Fig. 6.2.11. Week 11 - April 20, 2021.

Fig. 6.2.12. Week 12 - April 30, 2021.

HOME EXPERIMENT FIELD NOTES

Week One - February 6, 2021

The forms were coated on the interior and exterior with the moss slurry and protected under the eaves. They moss was green upon application and not much of the moss fell into the water in the tray.

Week Three - February 21, 2021

The tray was completely dry and refilled after this shot. Leaf litter has been blowing into the moss and substrate, removing some of the moss from the surfaces. The moss appears black and am not able to see many changes. The moss is wet to the touch and some pieces appear more green than the week prior. Water is clear.

Week Five - March 8, 2021

The pan was also dry this week. There seem to be darker splotches near to where the moss is hanging onto the substrate that could be protonema near the crevice. The clumps of moss are large and mostly dry, but are green in some areas. This could be larger fragmented moss that is living independently of attachment to substrate. Yellow-orange crystals are forming on the top.

Week Ten - April 11, 2021

The barnacles have been refilled mostly every other day and misted with water. Protonema is showing near the bases and in the interior. Under the surface of the ledge, dark green speckles grow more thoroughly. In the interior of the taller form near the house, protonema are showing up with a light green hue.

Week Eleven - April 20, 2021

A few crystals that remain at the tops of the ceramic substrate, however the ceramic substrate. Darker material has accumulated within the grooves. Two of the three forms show protonema growth in the interior. All have light green near the base, along shadows, and the southern, shadier sides of the barnacles. On the tallest form, the moss seems dried out and coated in dust. The mosses on the tall piece are densely clumped, appear dark, and have light tips. Light green is showing below the densely packed mosses on the substrate.

Week Twelve - April 26, 2021

Green color on interior form extends towards base. Sign of green filamentous material on northern facing piece. Small insect seen passing through.


Fig. 6.2.13. Protonema shown growing towards base of interior surface.


Fig. 6.2.14. Moss held in air bubble pocket and protonema trails into interior of form.

CLOSING SHOTS ON APRIL 30TH, 2021

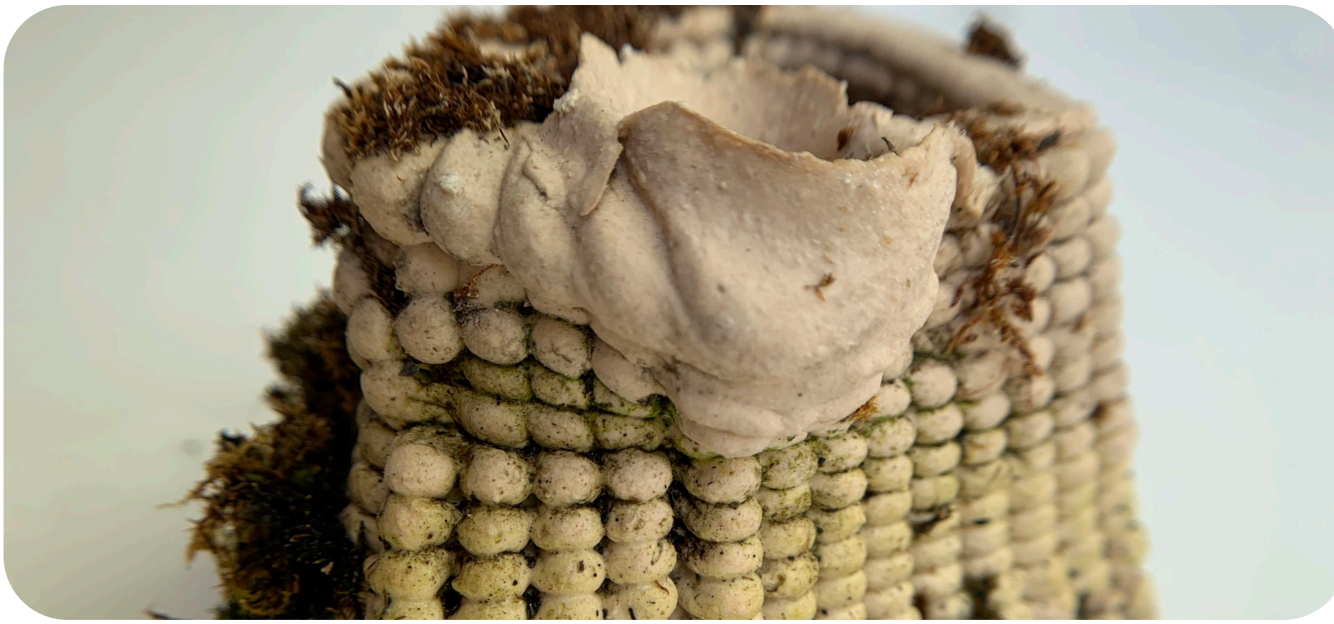


Fig. 6.2.15. Protonema growing best under overhang bubble and in grooves.

Fig. 6.2.16. Protonema growing out from densely packed mosses.

Fig. 6.3.0. Materiality of environment.

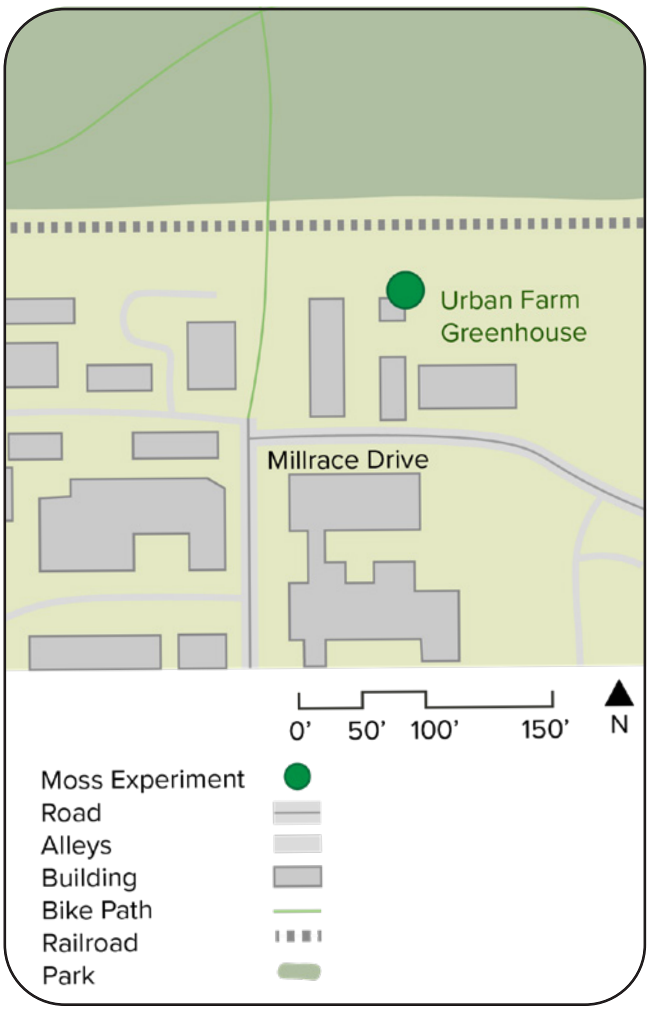


Fig. 6.3.1. Site context of experiment.

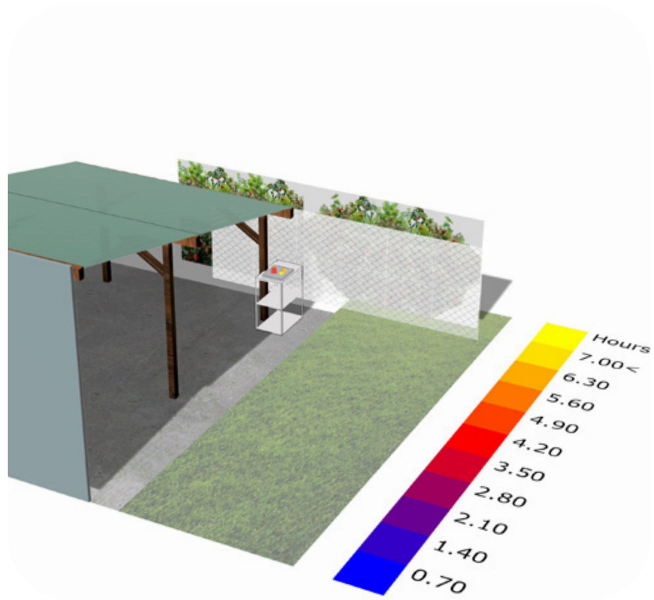


Fig. 6.3.2. Sunlight Hours Analysis (context).

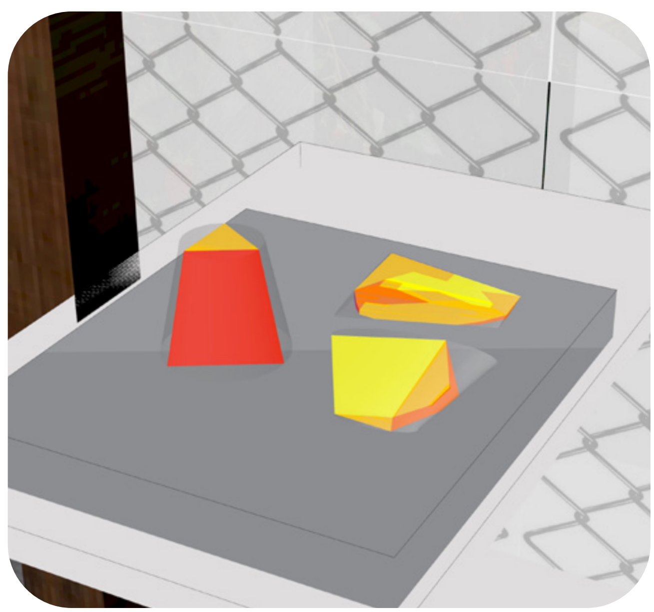


Fig. 6.3.3. Sunlight Hours Analysis (detail).

6.3 URBAN FARM, UNIVERSITY OF OREGON

The sunlight hours analysis measured exposure from 7am to 7pm on March 21st. The south-facing side of the interfaces received 4.2 hours of daylight, and the flattened areas received 5.6 to 7 hours of sunlight. The solar radiation analysis on the south-facing side of the interfaces received 21.6 kWH/m2 radiation, and the flattened areas received 18 to 24 kWH/m2 radiation. The eastern side showed the potential of receiving upwards of 27 kWH/m2. At 2pm on 3/15, midway through the experiment, the shadow analysis showed that the experiment was in a shaded environment.

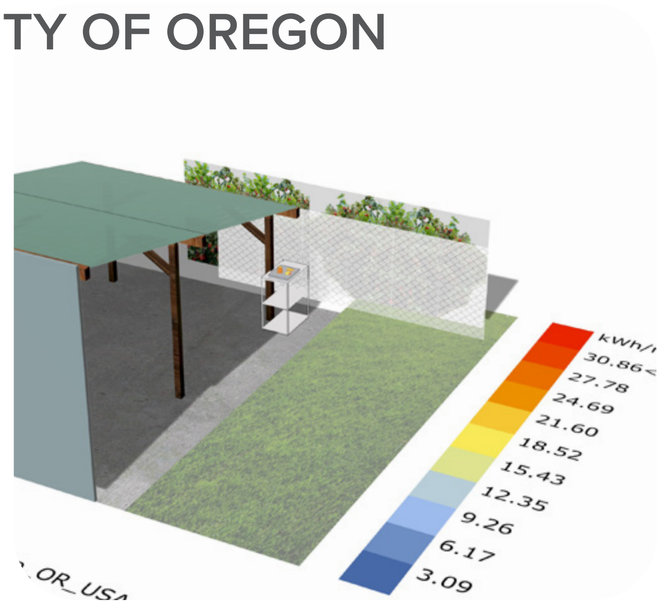


Fig. 6.3.5. Solar Radiation Analysis (context).

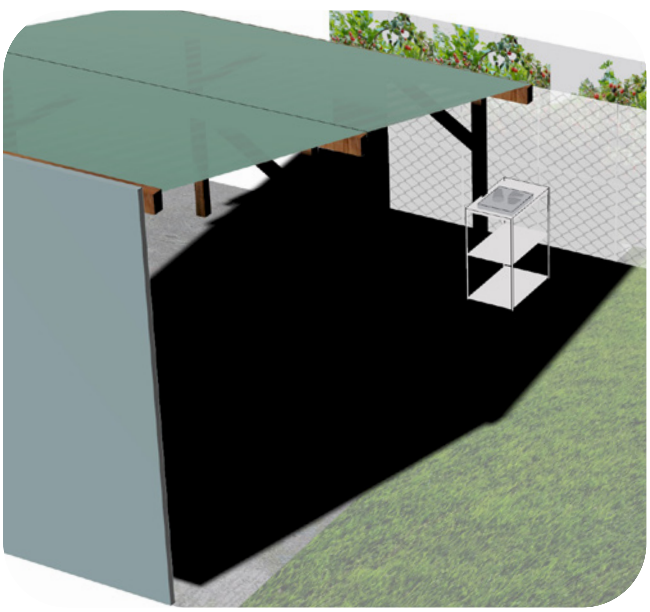


Fig. 6.3.4. Shadow Study at 2pm on 3/15/21.

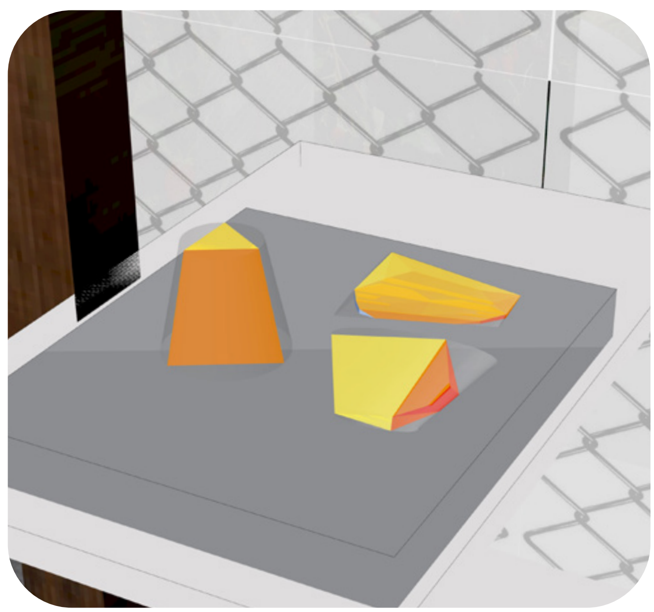


Fig. 6.3.6. Solar Radiation Analysis (detail).

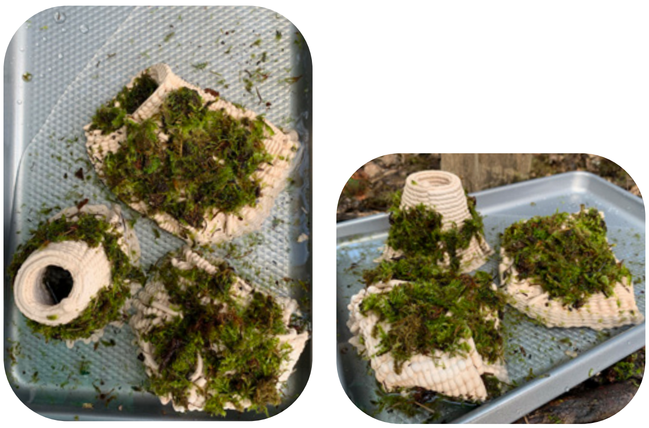


Fig. 6.3.7. Week 1 February 5, 2021

Fig. 6.3.8. Week 3 - February 21, 2021

Fig. 6.3.9. Week 5 - March 7, 2021

Fig. 6.3.10. Week 7 - March 19, 2021

Fig. 6.3.11. Week 9 - April 2, 2021

Fig. 6.3.12. Week 11 - April 16, 2021

URBAN FARM EXPERIMENT FIELD NOTES

Week One - February 5, 2021

This experiment was set up today and expect to have less control over this with refilling with water as the gate is locked. The three process experiments are placed here because it is protected and close to the train tracks where it may have exposure to pollution. The moss was green when it was first applied to the substrate.

Week Three - February 21, 2021

The tray was found wet. Lots of moss has fallen from the upright vessel. The majority of the moss has clumped and appears dead. It is uncertain if successful moss was still attached to the substrate.

Week Five - March 7, 2021

The tray was found with some moisture. There is strong evidence of squirrels disturbing the area with cracked walnuts spread on the cart and tray. Most of the moss at this point has fallen onto the baking sheet which I think is surprising because two out the three forms are quite horizontal.

Week Seven - March 19, 2021

The tray and mosses were found completely dried out. There is some pinkish discoloration near the upper part of the ceramic substrate. The tray was refilled with water after leaving.

Week Nine - April 2, 2021

The conditions remain similar to last week except for that more moss has fallen from the substrate. The baking sheet was found dry and refilled and misted with water. I scooted the substrates to the northern edge as that was the lowest point where more water would collect and filter through the substrate.

Week Eleven - April 16, 2021

There are few signs of salt on the ceramic substrate and mosses. Green and brown spots are located on the eastern side of the substrate. Moss seems to be holding on. There was a silver fish that dashed over the substrate when viewing.


Fig. 6.3.13. Week 11 - April 26, 2021

Week Thirteen - April 26, 2021
Surface on horizontal upper face has a yellow/ green hue. Yellow/hue alongside of of southern piece. Moss is thickly settled in places around tall piece. Yellow and brown on the mid-section of the tallest. Brown along the edge which appeared green two weeks ago.


Fig. 6.3.14. Old moss attachment near base with brown and greenish color an inch above

CLOSING SHOTS ON APRIL 26TH, 2021

Fig. 6.3.15. Green, likely protenema in innermost/shaded part of interface.

Fig. 6.3.16. Dried mosses collect in pockets near brown dusting.


Fig. 6.4.0 Materiality of environment.

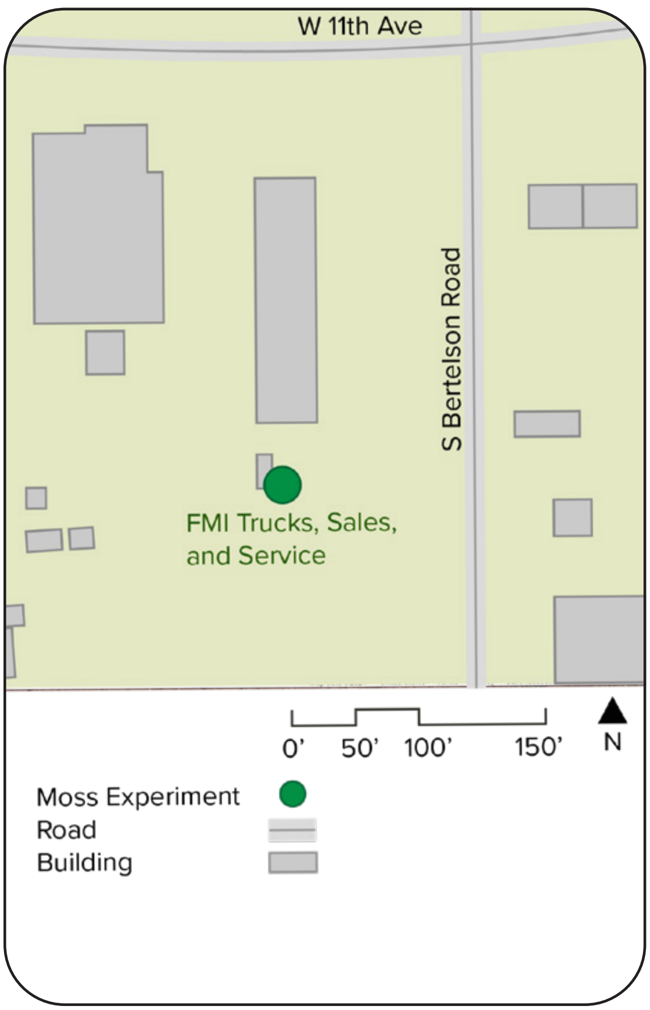


Fig. 6.4.1. Site context of experiment.

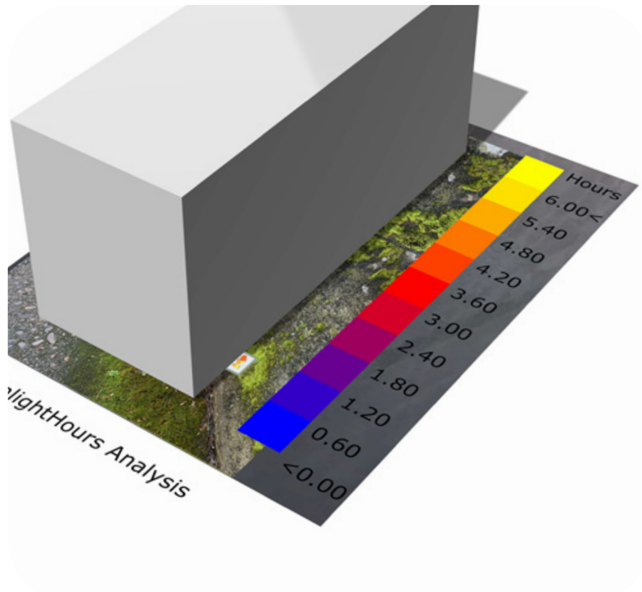


Fig. 6.4.2. Sunlight Hours Analysis (context).

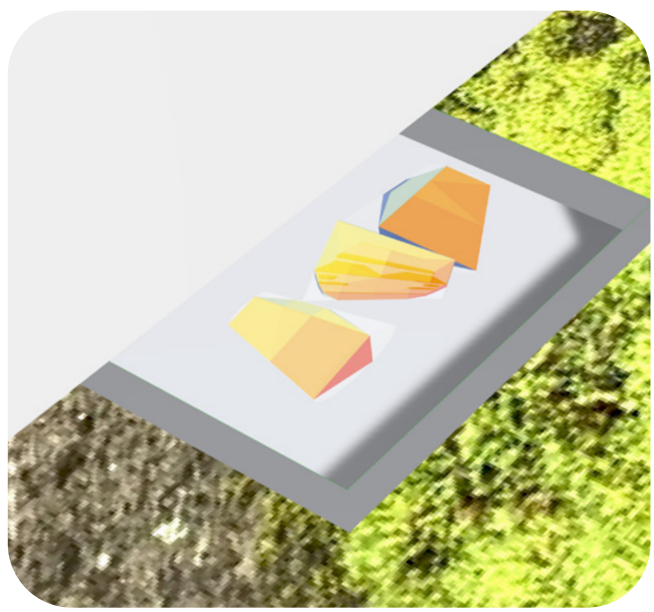


Fig. 6.4.3. Sunlight Hours Analysis (detail).

6.4 FMI SALES TRUCKS AND SERVICES

The sunlight hours analysis measured exposure from 7am to 7pm on March 21st. The east-facing side of the interfaces received 4.2 hours of daylight, and the flattened areas received 4 to 5.45 hours of sunlight. They received more than 6 hours and .6 hours on average. The solar radiation analysis on the east-facing side of the interfaces received 17 kWh/m2 radiation to 25.62 kWh/m2 radiation. The western side showed potential of receiving upwards of 19 kWh/m2. At 2pm on 3/15, midway through the experiment, it was in a shaded environment.

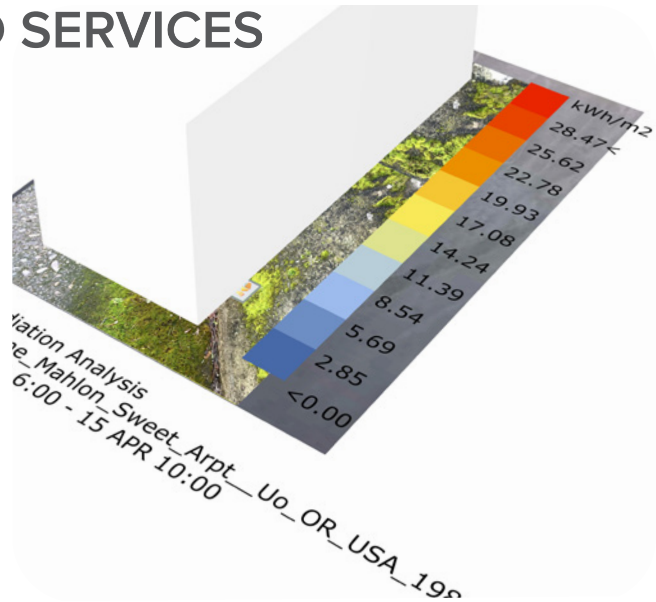


Fig. 6.4.5. Solar Radiation Analysis (context).

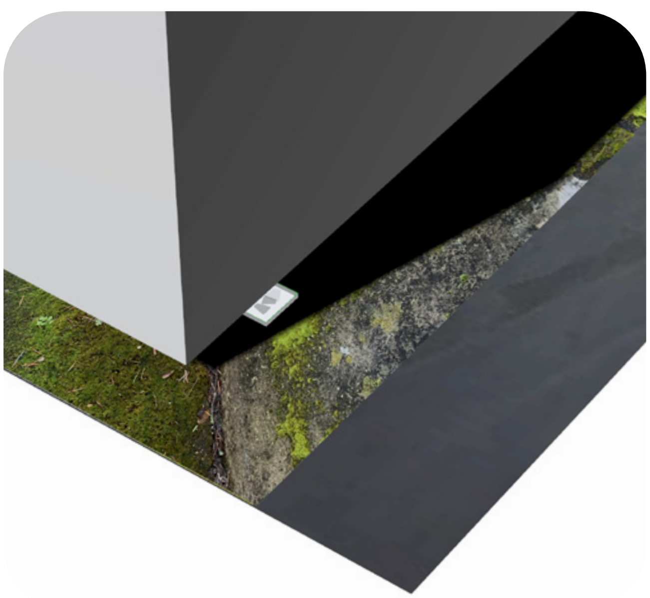


Fig. 6.4.4. Shadow Study at 2pm on 3/15/21.

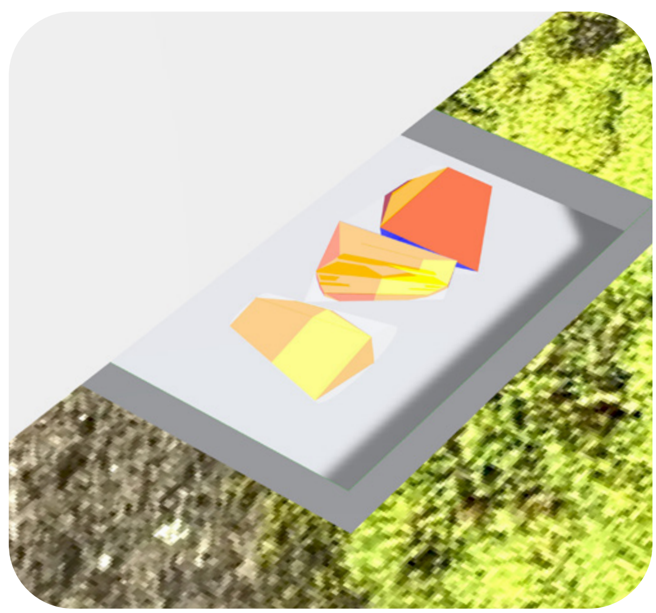


Fig. 6.4.6. Solar Radiation Analysis (detail).

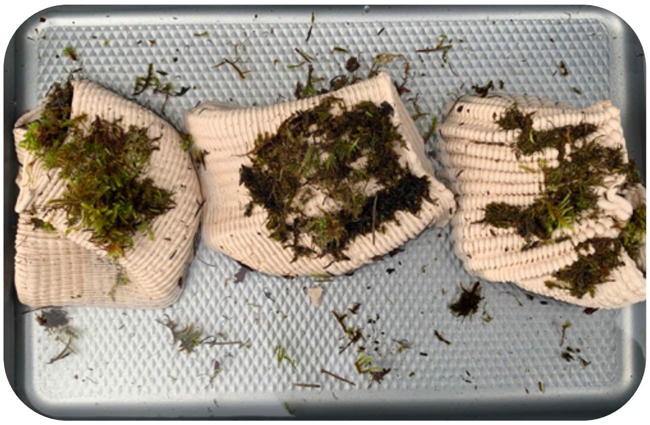


Fig. 6.4.7. Week 1 - February 8, 2021.


Fig. 6.4.10. Week 8 - March 29, 2021.


Fig. 6.4.8. Week 3 - February 22, 2021.


Fig. 6.4.11. Week 9 - April 2, 2021.


Fig. 6.4.9. Week 5 - March 8, 2021.


Fig. 6.4.12. Week 10 - April 16, 2021.

FMI EXPERIMENT FIELD NOTES

Week One - February 8, 2021
Set up experiment under trailer's edge in baking sheet of water. I applied the moss with the same moss mixture and slurry as applied for the others.

Week Three - February 22, 2021
There are bits of green that are showing above the wet clumps of moss.

Week Five - March 8, 2021
The mosses seem to be dried out! They are less attached and little bits have collected on the central piece at the top. The moss seems to be suffering from dryness. The mosses on the right piece are settling into a major groove.

Week Eight - March 29, 2021
Water appears cloudy and unsure if the moss is hanging on to the substrate. A green spot has appeared on a lower part of one of the pieces. Even through dry, some of the moss seems lighter in color.

Week Nine - April 2, 2021
A glow of green has formed between all three of the pieces and along the underside. The pan was dried out and refilled an misted after this visit.

Week Ten - April 16, 2021
There are signs of light green growing on each piece. There are a few speckles of salt. When moistened with the mister, the moss does not turn green, but seems to respond by turning slightly lighter in color and moving to stick out. There is also indication of green on the western side where there is no sun exposure.

Week Twelve - April 30, 2021
The original moss is very dry. Protonema that was green looks like a dusting on all forms. The green is brightest on the interior surfaces and grooves. Moss on top seems attached and bound to ceramic. The green seems to grow near where another surface is located.

Fig. 6.4.12. Week 12 - April 30, 2021.

Fig. 6.4.13. Protonema shown growing best near another surface and near water access.

.

Fig. 6.4.14. Yellow salt crystal growth near rim and shaded area where protonema takes up grooves.

CLOSING SHOTS ON APRIL 30TH, 2021

Fig. 6.4.15. Protonema growing near shaded areas and grooves.

Fig. 6.4.16. Protonema gain shown in grooves near moss fragment.

Fig. 6.5.0. Amazon Park Eugene, OR.

APPLICATION TYPES:	HORIZONTAL	DIAGONAL	VERTICAL	DYNAMIC	FIXED
1. Tree Grate	—	/		//	⊥
2. Rooftop	—	/			⊥
3. Screen		/	|		⊥
4. Channel		/	|		⊥
5. Billboard		/	|	//	⊥
6. Bench	—	/			⊥
7. Bollard		/	|		⊥
8. Median	—	/	|		⊥
9. Downspout	—	/		//	⊥
10. Lighting	—	/	|	//	⊥

Fig. 6.5.1. Ceramic/moss bricks suitable for a range of landscape applications from serving as urban furniture for public transit to illuminating resting areas in private spaces.

During the fall, when taking the Research by Design studio, with a focus on moss research, I investigated potential applications for ceramic and moss interfaces. The concepts were brought forward from the collection of ten interfaces designed for the experiment. When taking a walk around my neighborhood in south Eugene, I looked for areas where there could be a benefit to the urban infrastructure, ideally located near a water source or low-light conditions as seen in Figure 6.5.0. The typologies identified explore their application on horizontal, diagonal, and vertical surfaces and consider dynamic or fixed attachments, as seen in Figure 6.5.1.

6.5 SPECULATIVE DESIGN

Fig. 6.5.2. Tree Grate.

1. Tree Grate. The tree grate functions well on horizontal and diagonal surfaces and can shift over time with the movement of the treeas seen in Figure 6.5.2. The moss attachment near the roots of the tree aid in nutrient cycling with exchanging nitrogen. With moss being the first to receive air particulates and water, it is a wonder filter of pollutants. The unique forms create a cooler microclimate in comparison to other conventional materials and serve as a habitat.

Fig. 6.5.3. Rooftop.

2. Rooftop. This rooftop typology functions well on horizontal and diagonal surfaces and works best with a fixed attachment to existing roof materials as seen in Figure 6.5.3. The fire-retardant properties of moss protect the building and infrastructure from the threat of fire. The moss layer can protect underlying materials from UVB radiation and prevent structural damage. With moss being the first to catch rainwater, it filters, slows, and reduces runoff. This substrate is a lightweight material the requires minor retrofitting for an application and works well in small spaces.

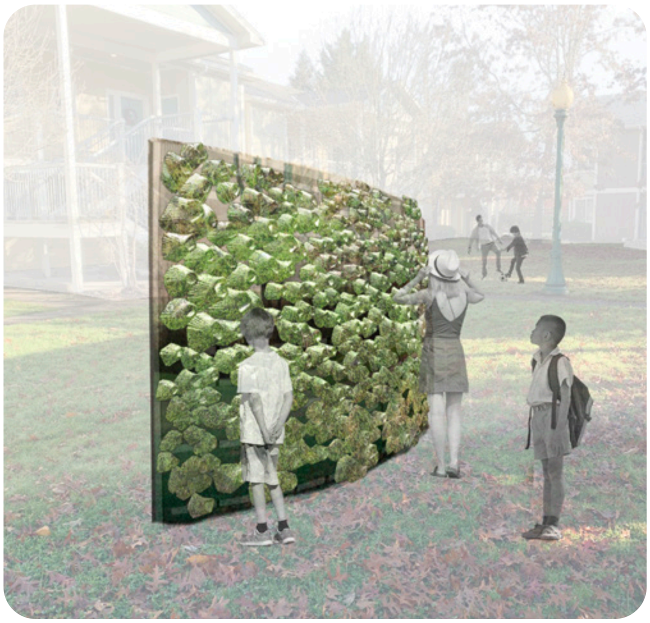


Fig. 6.5.4. Screen.

3. Screen. The screen functions well on diagonal and vertical surfaces with a fixed attachment to the ground plane, as seen in Figure 6.5.4. The two-sided screen creates visual interest and can function in a range of spaces for creating rooms. This screen works well in both public and private applications and small spaces such as alleyways. The impact of a larger surface of the screen can reduce air temperatures and add biodiversity. A significant benefit includes reducing noise being absorbed by both moss and ceramic surfaces. The screen serves as a community attractor and place-making piece.

Fig. 6.5.5. Channel.

4. Channel. The Amazon Creek is channelized with concrete walls, and this application is suitable on vertical and diagonal surfaces with a fixed attachment, as seen in Figure 6.5.5. The textured ceramic infrastructure that holds moss increases surface area, and the water can be effectively filtered to aid in flood control. This is a low maintenance and passive application. The unique surfaces can enhance riparian biodiversity. This application can help absorb noise from nearby traffic. The moss supported by the moist environment can additionally help cool the air temperature.

5. Billboard. The billboard functions well on diagonal and vertical surfaces with a fixed or dynamic attachment, as seen in Figure 6.5.6. The visibility of the billboard can be an effective tool for sharing the potential application, benefit, and impact of mosses to the greater community. The billboard also acts as a sound buffer. The added green space supports mental health. The low maintenance billboard is resilient after period of low humidity. The lack of commercialized messaging on this designated surface can be a breath of fresh air and attractive for greening the urban fabric.

Fig. 6.5.6. Billboard.

6. Bench. Applications under the bench work well on a horizontal or diagonal surface and are recommended for a fixed attachment, as seen in Figure 6.5.7. Surfaces under the bench are sheltered from light, assisting in aid of moss growth. This is an example of how out-of-reach places can have greater potential with a design intervention. With a highly interactive bench and space for exchange, the pieces hold the potential to be interactive and as places where people might exchange notes or other tokens to create surprises in the community fabric.

Fig. 6.5.7. Bench.

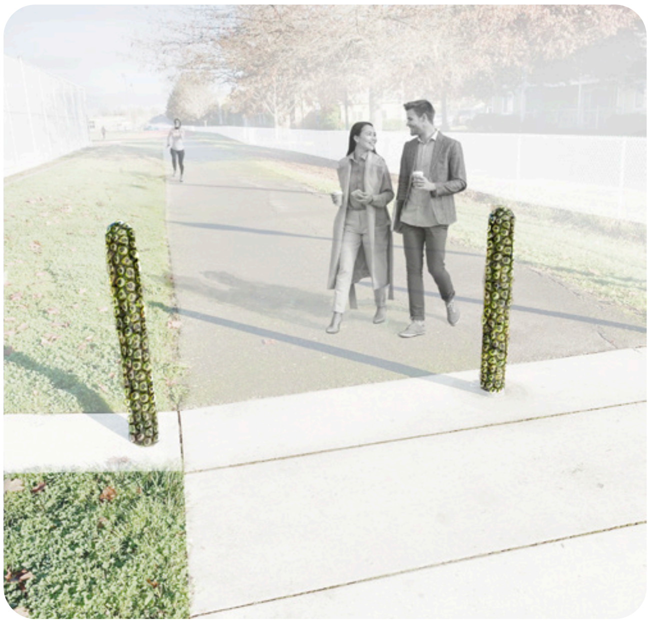


Fig. 6.5.8. Bollard.

7. Bollard. The bollard functions well on diagonal and vertical surfaces with a fixed attachment, as seen in Figure 6.5.8. Existing bollards can be enhanced with a new application with ceramic and moss interfaces. The simple embellishment on a smoothed surface can significantly impact increased surface area and the ability to filter water. The bollard is a piece of landscape infrastructure that is not commonly defaced or tampered with and is simple in aesthetic value. There is great potential for enhancing the design of bollards to increase aesthetic and ecological value.

Fig. 6.5.9. Median.

8. Median. Applications for the median are possible on horizontal, vertical, and diagonal surfaces and are recommended for a fixed attachment, as seen in Figure 6.5.9. The medians are a marginal space that human or animal visitors do not commonly frequent. These marginal typologies are spaces that are typically under-designed or unplanted and could receive more attention for remediation. The emissions and particulates deposited by traffic can be filtered with the activation of mosses.

9. Downspout Filter. The downspout functions well on diagonal and horizontal surfaces with a fixed or dynamic attachment, as seen in Figure 6.5.10. The forces of water moving through the downspout can erode the soil. The application of the downspout with a hard surface can reflect the water and prevent direct erosion. The slowed infiltration of the water also reduces and filters runoff. The unexpected visual interest in the garden is enhancing, and the forms can be redesigned in ways that direct water away from the home to desirable gardens.

Fig. 6.5.10. Downspout Filter.

10. Lighting. Applications for the lighting are suitable on horizontal, vertical, and diagonal surfaces with fixed and dynamic attachments, as seen in Figure 6.5.11. Lighting holds the possibility to be hyperfunctional in reducing runoff and enhancing habitable spaces. The lighting can be modular and economical, tailored to a range of contexts. This type of lighting is helpful for private and public settings and adds valuable green space. Lighting is often viewed as a kind of hard infrastructure, and this softened infrastructure adds a new way of conceiving hyperfunctional fixtures in

Fig. 6.5.11. Lighting.

Fig. 6.6.0. #7 Ceramic interface where protonema is shown growing in the interior where it receives solar radiation.

6.6 META-ANALYSIS

Meta-analysis of Main Experiment

Purpose

The main experimental design of the four total experiments produced in this Master's Project inquired about repeated forms on four unique substrates in a residential setting. This main experiment was the most rigorous of the four conducted experiments because it explored the formal design characteristics of the designed barnacle substrates individually, as a group of ten unique designs, four unique substrate groups, and additional process work.

Approach

This quasi-experiment was set up on Sunday, January 31st, and ran through April 27th, 2021. The experiment was a quasi-experiment because all forms and groups within this experiment did not have a control and all the observations and treatments were done in the same manner. The substrates included from south to north ten clay substrates mixed with 7% moss, ten ceramic pieces composed of 10% burnt-out sawdust, ten ceramic pieces composed of 5% burnt-out sawdust, ten ceramic-only pieces, and fourteen process pieces composed of ceramic. The ceramic material was purchased from Georgie's Gmix at 6.7pH and was hand-mixed with a kitchen-aid mixer at a ratio on average of 1.75 grams of clay to 1 ml of water. The clay material was fired to cone 07 in an electric kiln, and the fired ceramic material was 6.8 pH. The ceramic material was mixed with sawdust to burn out during the firing to create different porosities. The work was designed parametrically in Grasshopper, taking inspiration from barnacle structures for resting on a horizontal surface. Each of the four groups of ten was arranged separately in the same pattern within individual metal trays on a residential wooden deck. The trays were filled with water weekly and misted with water vapor. The trays were filled with water so that the ceramic would absorb the water to help the mosses metabolize. At least four known moss species, including Didymodon vinealis, Antitrichia californica, Didymodon vinealis, and Ceratodon purpureus were chopped and mixed with a water slurry and hand-pressed on the ceramic substrates. For the experiment's three-month duration, photographs were taken with an iphone from plan, axon, and detailed perspectives. The experiment was also documented hourly from an axon vantage point from a camera programmed by raspberry pi. A Govee hygrometer measured the temperature and humidity to compare the environmental conditions with the results from the experiment.

Implications

The set-up of the experimental design changed quickly at the outset during a heavy rain that removed much of the moss application from the substrate. The substrates were subsequently moved under the eaves to protect the moss application from direct rainfall. The decision to shelter the mosses from direct rainfall eventually affected the build-up of crystals, especially near the upper part of the tallest forms. The white salt built up most intensely on the substrates with the highest porosity of 10% sawdust burnout. To the touch at the tops of the forms during week ten, the ceramic crumbled. According to Bruce McCune, a bryologist at Oregon State University, the ceramic was compromised because the evaporation exceeded runoff. If the pieces received greater runoff, the salt would wash away. The salt accumulation was problematic because of the weakened structural integrity of the ceramic forms; salt is a known deterrent to moss growth. Mosses exist in many different conditions worldwide, but do not perform well in salty conditions, so increasing runoff, whether through heavier misting periods or rain exposure, once established would be necessary.

While the applied mosses continued to fall from the ceramic substrates, as early as week two of the experiment, some of the mosses appeared to move inwards into the ceramic substrate's grooved areas for attachment. The mosses lost their bright green appearance during the first application, changing darker in color by the second week. After misting with water vapor, the mosses appeared lighter in color at the tips. Some of the tips of the mosses exhibited salt crystals as well. The mosses that held on to the substrate adhered to the mid-section of the pieces, likely due to the optimal grooved pattern on 3-7mm amplification thickness. The mosses also formed a string-like or grouped attachment, forming a general pattern language for the moss attachment. Towards the top of the grouped moss attachment, the mosses appeared to peel away at the top. Some of the moss attachment occurred in the interior of the forms, but overall attached more strongly along the exterior of the forms. In general, it seemed that the steeper and longer the slope of a facet, the moss was less likely to attach than the slopes that were shorter and greater in groove depth.

Findings from the Govee sensor show that the average temperature where the experiment took place was at 47 degrees in February, 51 degrees in March, and 52 degrees in April, rising over time. The average relative humidity where the experiment took place was at 76% degrees in February, 64% in March, and 56% in April, dropping over time. The correlation between temperature and humidity demonstrated an inverse relationship of increased temperature to a drop in humidity during midday. The humidity was generally higher at night when the temperatures dropped. There was less sunlight during winter's cloudier conditions and further into the experiment increased direct light hit the experiment. During week eleven of the experiment, a sweet gum tree growing southeast of the deck provided more consistent shade and cooler temperatures. During the midpoint assessment of the experiment, the attachment of the mosses was not correlated with a certain aspect. During week eight, there was evidence that the ceramic substrate was turning darker. Into week nine, it was apparent that a light green hue was showing up at the bases near the bases on the process forms. This happened first on the process forms because a plastic bag shielded the tray from light throughout the morning. The light green filamentous material was the protonema phase, showing the first stage of moss growth. Moss growth showed within all trays except for the unfired clay tray. The protonema typically grew towards the base, near the old moss coverage, in the interior of the medium height pieces, and along areas that received less sun between pieces. This was slightly surprising because much effort went into designing the grooves for the forms for moss attachment, expecting the mosses to propagate under the moss application. However, the new moss growth appeared to occur where the moss is not attached. This could also be the case that protonema was growing under the moss attachment but was not visible.

This experiment has shown that over the duration of two and half months, that protonema growth was apparent and was proof that new mosses were invited to grow in areas where there was most shade and water movement. This can be taken forward with new design work that shows structural integrity to the ceramic pieces, where water runoff occurs and shade is apparent.

Limitation

The shorter timeframe of the experiment showed that the moss growth was still in the first stages of development, and with an extended period of testing, the results would have been more complete.

This deck area was likely too sunny with the southeast-facing orientation and would have been better if placed in a less sunny setting. Site selection was limited to want to protect the experiment from human and animal intervention, having access weekly, and general lack of accessible spaces with COVID-19 restrictions. The Govee monitor was disconnected from the internet at certain times, so all data during the experiment was not recorded. The Rasberri Pi suffered a weak attachment to the wall, which did not accurately record images from the same vantage point for the entirety of the experiment.

Meta-analysis of Home Experiment

Purpose

The purpose of the Home experiment on Patterson Street served as additional information to the Main experiment and compared to the other two satellite experiments. This experiment was set up to test moss growth in a different residential area of Eugene, Oregon. The conditions of the home experiment were the most accessible for observation and maintenance through refilling the pan with water and misting it with water vapor.

Approach

The experiment was a quasi-experiment because the substrate experiment did not have a control, and the observations and treatments were done in the same manner. This quasi-experiment was set up on Tuesday, February 6th, and ran through April 27th, 2021. The three uniquely formed substrates were composed of ceramic and were development pieces for producing the main experiment. Because they were process pieces from design development, they have imperfections from a collapse, an air bubble, and layer deposition attachment and are unlike any other forms. The ceramic material was purchased from Georgie's Gmix at 6.7pH and was hand-mixed with a kitchen-aid mixer at a ratio on average of 1.75 grams of clay to 1 ml of water. The clay material was fired to cone 07 in an electric kiln and changed the pH to 6.8. The three forms were situated together in a tray on a concrete patio and below an upper deck. The tray was filled with water and misted with water vapor on a weekly basis. Halfway through the experiment, the tray was refilled with water daily and misted with water vapor. The tray was filled with water so that the ceramic would convey the water upwards to help the mosses metabolize. For the duration of the experiment, photographs were taken with an iPhone from plan, axon, and detailed perspectives.

Implications

The application of the mosses stayed on relatively well for the first several weeks of the experiment. The wind exposed the experiment to swirling oak leaves, impacting the attachment of the mosses to the substrate. As early as a month into the experiment, brown speckles appeared on the concaved areas of the substrate. Two months into the experiment, the brownish speckles turned into green on the interior of the mid-sized piece oriented south, closest to the building. This green filamentous material also emerged near the forms' bases and along the concave forms on all three substrates. It was interesting that the moss growth appeared at the base. Perhaps the fallen moss in the water attached and, with the help of the water movement, ascended the baseline of the water. The moss on the southern-most form attached the most densely over time. The original moss application of the exterior showed that protonema growth was emerging directly under the moss attachment.

On the exterior of the northern-most substrate, the original speckles and moss clump showed a dried attachment which could have been due to salt crystals interfering with the moss development. Only a few salt crystals developed on the forms and range in color from white to yellow-orange. The salt crystals showed no sign of compromising the structure of the ceramic substrate. The reduced salt crystal development could have resulted from regular misting and hydration that allowed the salt crystals to disappear.

This experiment exhibited the earliest signs of moss growth and the most moss growth from near the base, interior, and under the applied mosses. With regular misting of water vapor and hydration, the ceramic substrate held composure. The information generated from this experiment could be taken forward with successful results by ensuring that the pieces are exposed to regular misting and hydration to activate the moss and wash away salt crystals.

Limitation

The shorter timeframe of the experiment showed that the moss growth was still in the first stages of development, and with an extended period of testing, the results would have been more complete. Less environmental data was collected from this site. This experiment lacked a temperature and humidity sensor and time-lapse.

Meta-analysis of Urban Farm

Purpose

The purpose of the experiment on campus at the Urban Farm at the University of Oregon served as additional information to the Main experiment and as a comparison to two other satellite experiments. The Urban Farm experiment site was of interest for its proximity to a railroad track, a productive garden, and large park area. While the experiment was protected in a locked space, the experiment was also the least accessible for observation and for maintenance of refilling the pan with water and misting it with water vapor.

Approach

This quasi-experiment was set up on Friday, February 5th, and ran through April 27th, 2021. The experiment was a quasi-experiment because the substrate experiment did not have a control, and the observations and treatments were done in the same manner. The three uniquely formed substrates were composed of ceramic and were development pieces for producing the main experiment. Because they were process pieces from design development, they had deviations from the design of the main experiment. Two forms had flat surfaces and shallow grooves that formed during the collapse, and the third was an upright positioned piece that possessed similar characteristics to barnacle #5. The ceramic material was purchased from Georgie's Gmix at 6.7pH and was hand-mixed with a kitchen-aid mixer at a ratio on average of 1.75 grams of clay to 1 ml of water. The clay material was fired to cone 07 in an electric kiln and reached 6.8pH after firing. The three forms were situated together in a tray on the top shelf of a metal cart. The cart was placed near the eastern edge of an open pavilion. To the north of the experiment, a chain-linked fence and blackberry vegetation served as a barrier. The cart was otherwise exposed to the elements around the pavilion. The tray was filled with water and misted with water vapor on a bi-weekly basis. The tray was filled with water so that the ceramic would convey the water upwards to help the mosses metabolize. For the duration of the experiment, photographs were taken with an iPhone from plan, axon, and detailed perspectives.

Implications

After the first week of the experiment, significant quantities of the moss had fallen into the tray. The pavilion roof was high, which allowed for wind and rain to interact with the substrates. There was also early evidence of squirrel activity with walnuts having been left around the tray. By week seven, there was slight discoloration in the upper parts of the ceramic substrate, like a precursor to salt crystals. The mosses had dried out between many visits. Because of their dry state, the low point of the tray was towards the northern side of the cart, so the substrates were pushed into the lower space for collecting water for more extended periods. During week eleven, there was evidence of green and brown spots located on the eastern side of the substrate, a sign of protonema, the first stage of moss growth. A silver fish was noted to have dashed over the pieces showing potential spore transfer from small organisms.

Limitation

The shorter timeframe of the experiment showed that the moss growth was still in the first stages of development, and with an extended period of testing, the results would have been more complete. Access to the site for observation and maintenance was restricted due to the locked greenhouse area. Less environmental data was collected from this site. This experiment lacked a temperature and humidity sensor and time-lapse. *Meta-analysis of FMI Truck Sales and Service*

Purpose

The purpose of the quasi-experiment at FMI Truck Sales and Services served as additional information to the Main experiment and as a comparison to two other satellite experiments. The FMI Truck Sales and Services experiment site was of interest for its proximity to an industrial area, where pollutants were likely higher in concentration. While the experiment was protected in a locked space over the weekend, the experiment was accessible weekdays for observation and for maintenance of refilling the pan with water and misting it with water vapor.

Approach

This quasi-experiment was set up on Monday, February 8th, and ran through April 27th, 2021. The experiment was a quasi-experiment because the substrate experiment did not have a control and the observations and treatments were done in the same manner. The three uniquely formed substrates were composed of ceramic and were development pieces for producing the main experiment. Because they were process pieces from design development, they had deviations from the design of the main experiment. All three forms had flat surfaces and varying groove depths that formed during the collapse. The ceramic material was purchased from Georgie's Gmix at 6.7pH and was hand-mixed with a kitchen-aid mixer at a ratio average of 1.75 grams of clay to 1 ml of water. The clay material was fired to cone 07 in an electric kiln and reached 6.8pH after firing. The three forms were situated together in a tray directly on asphalt, which supported a thick sheet of moss growth. The tray extended out 3 inches to the east from a truck that stood 5" above the tray. This area was part of a parking lot and often had parked cars within a few stalls of the experiment. The tray was filled with water and misted with water vapor on a bi-weekly basis. The tray was filled with water so that the ceramic would convey the water upwards to help the mosses metabolize. For the duration of the experiment, photographs were taken with an iPhone from plan and detailed perspectives.

Implications

During week three of the experiment, pieces of wet moss perked up above the other pieces of moss. By week five, the mosses had settled into the lower parts of the forms. More bits of the mosses had fallen into the tray. By week eight, the water seemed to be cloudy. A green spot, likely signs of protonema, had developed on one of the lower parts of the pieces, and by the end of week eight, green protonema showed signs of growth near the bases and adjacent surfaces on all the forms. The dried mosses appeared light in color. At week ten, the bright protonema color continued to mature and showed greater growth on the western side of the forms, where there is very little sun exposure.

Limitation

The shorter timeframe of the experiment showed that the moss growth was still in the first stages of development, and with an extended period of testing, the results would have been more complete. Access to the site for observation and maintenance was restricted to weekdays, with business being closed on the weekends.

Less environmental data were collected from this site. This experiment lacked a temperature and humidity sensor and time-lapse.

Fig. 6.6.1. Barnacle Interface #3 where ceramic shows green protonema under moss growth as a response to the presence of moss.

	Main Experiment	*Home Experiment*	*Urban Farm*	*FMI Truck Sales*
Form Type	Designed/Undesigned	Collapsed	Collapsed	Collapsed
Number of pieces	56	3	3	3
Substrate	Clay and moss, burnt-out sawdust of ceramic 5%, 10%, ceramic	Ceramic	Ceramic	Ceramic
Maintenance	Weekly	Daily to Weekly	Bi-weekly	Bi-weekly
Materials	Wood deck	Concrete patio	Steel cart	Moss bed on asphalt
Elevation	8.5 feet	Ground	2.67 feet	Ground
Aspect	Southeast	North	East	East
Moss Retention	Mid-section	Pockets, mid	Depression	Depression
First sign of growth	No	Yes, on interior	No	No
Most moss growth	Yes	Yes	No	No
Moss Growth	Near water	Interior	Near base	Near base
Moss Color	Bright green	Bright Green	Brown-green	Dark Green
Unknown Growth	Yes, cotyledons	Yes	Yes	Yes
Salt Crystals	Yes - destructive	Yes, orange	Yes	Yes

Fig. 6.7.0. Results for each experiment set-up extracted from meta-analysis.

6.7 PROCESS DISCUSSION

Purpose

The purpose for conducting experiments with four types of substrates in one location and testing the same substrate across three locations through a quasi-experiment was to generate more information for developing a design framework. Even though the experiments were conducted simultaneously using similar substrates and conditions, the observation and maintenance rates varied. If only the Main experiment was tested, the results would have been limited to the factors around the one experiment. These experiments show that different environmental conditions, maintenance regimes, and substrates matter for designing effectively with ceramic substrate and mosses.

Approach

The forms and surfaces across the experiments can be divided into two groups: the undesigned and the designed substrates. The undesigned substrates are the process pieces of failed pieces of the experiment and lack measurability in their form. The designed substrates were the goal of the first prototyping process for setting up the Main experiment to compare the same designed form against other designed forms with different substrates. The designed forms range in amplification in thickness from 10mm at the base to a gradation in reduced amplification to 3mm at the top. The largest build volume is the #1 interface measuring at 113 x 121 x 145mm and the smallest build volume is #5, measuring at 104 x 106 x 100mm. The designed forms were shaped conically with apertures to collect more rainwater and create an interior and exterior environment. The undesigned substrates vary in surface texture and dimensions, and most are the result of deformed or collapsed designed substrates. The undesigned substrates part of the Main experiment showed some of the earliest protonema growth compared to the designed substrates. However, some of the greenest areas of the designed substrate are within the designed substrate of the Main experiment. It is difficult to tell if the designed or designed experiments show the greatest promise.

The substrate compositions varied the most for the Main experiment and sought to test for porosity, clay, and ceramic substrate. The clay pieces were ineffective for growing moss and suffered from severe alteration from one rain event. The ceramic porosities of 10% and 5% sawdust burnout were the slowest to show the protonema stage, but this could have been due to the sunnier conditions. The process pieces and straight designed substrate of 10 showed the greatest amount of protonema development. The Home experiment was the first to show protonema growth in the interior. Thirdly, the FMI experiment showed the second and greatest amount of protonema coverage into the eleventh week. The Urban Farm experiment was the last to show signs of protonema growth.

Environmental conditions were considered by placing the experiments in two different residential areas, on campus at The University of Oregon near a park and railroad, and in an industrial area west of Eugene. Because of the placement of the experiments in Eugene, Oregon, they experienced relatively similar weather conditions such as temperature, airflow, and wind. The Main experiment received greater southeastern exposure; the Urban Farm and FMI experiments received greater eastern exposure; the Home experiment received greater northern exposure. The Home experiment received the greatest frequency of maintenance by watering the tray and misting water vapor on the ceramic pieces weekly and halfway through the experiment on an as needed or daily basis. The Main experiment received the most consistency in maintenance by watering the trays and misting water vapor weekly. The Urban Farm and FMI experiments received the least amount of maintenance through biweekly filling trays and misting with water vapor. There was a strong correlation between the maintenance of the experiments and the observation of the experiments. The Main experiment was documented weekly in plan view, axon view, and hourly from a time-lapse. The Home experiment was documented less regularly in photography but was monitored more closely with greater access to the pieces. The Urban Farm and FMI experiments were monitored on an average bi-weekly basis.

Materials surrounding the experiments and elevation differed for each context. The Home experiment was elevated on a second-floor deck with mostly wood and painted wood surrounding the environment. The Home experiment was set on a concrete patio at ground level and protected more thoroughly with coverage from the eaves.

The Urban Farm experiment was relatively exposed with a higher canopy and was elevated on a metal cart. The FMI experiment was placed directly on the ground on asphalt already covered with mosses. Based on the locations and materiality surrounding the experiments, it the resulting disturbance from surrounding microbes, insects, and animals likely played a role in how the mosses attached to the substrates. Insects were noted to have been found around the Home experiment and at the Urban Farm. Also, at the Urban Farm, walnuts left behind by tampering squirrels on the tray show higher level disturbance. At the Main experiment, there were signs of moths and spiders. At FMI, less evidence of smaller movement was recorded.

Implications

The results of the three-month experiment show that it is possible to design ceramics through 3D printing with clay and for the propagation of protonema, the first stage of moss growth. A few considerations need to be considered when moving the design forward, including moisture, form, protection, efficiency, and substrate.

The design of the form has an impact on moss growth. For the forms of the main experiment, the moss showed first growth on undesigned substrates near the bases. Horizontal forms do not necessarily hold moss better than vertical substructures. The designed vertical forms with deeper grooves held applied mosses better over time, and undesigned horizontal forms with fewer grooves lost more mosses. It seemed that moss grew best near the base and waterline throughout this experiment, moving upwards on the substrate. The shorter ceramic substrates with larger groove depth and less slope exhibited the most performance. Because the fragmented mosses had difficulty attaching to the sides of the substrate, it would be beneficial to create forms with a greater surface area that hold moss and moisture with pockets and double walls. The greater surface area can also cast shade to augment conditions favorable for moss growth.

It is optimal to have consistent irrigation and suitable environmental conditions with elevated relative humidity at the outset. Ideal conditions for propagating moss are suitable at 70% relative humidity fluctuating between 40-80% relative humidity. Optimal conditions for the experiment would be at the beginning of winter in the Pacific Northwest. It is beneficial if the substrate remains moist for the duration of the experiment, so watering and misting the substrate for the first sixty days is crucial for moss growth. The first moss growth appeared near the waterline within the tray, suggesting that water movement is also essential for propagating the mosses. Consistent watering increases runoff and washes away the accumulation of salt crystals is crucial for reducing evaporation rates and restoring the integrity of the substrate.

Controlling the material quality of the substrate and environment can be optimal for future designs. Ceramic bisqueware underfired to cone 07 with no additives exhibited the optimal porosity to maintain structural integrity and convey water efficiently with a ceramic pH of 6.7. Greater porosity of the 5% and 10% sawdust reduces the structural integrity of the work and moss propagation with the increased formation of salt crystals. The proximity to plants likely assists with increasing the biodiversity within the mosses and assists in spore dispersal. Reducing tampering from smaller animals such as squirrels and increasing exposure to smaller insects can assist with the transportation of spores.

Protecting ceramic and moss designs with material above and laterally serves two purposes; to block light and soften the impact of direct precipitation and wind. With material coverage, this creates low lighting conditions proved to be significant at the beginning of the experiment while mosses attach. During extreme wind and rain events, this can slow direct forces that could easily remove moss attachment. Especially with applications at higher elevations that experience greater wind forces, reducing the wind and drying impact is important. The variations within the experiment setup did not show a strong correlation in aspect. However, it can be assumed that placing the experiment near the north sides of buildings or materials can reduce solar impact. On a smaller scale, the application of screens, meshes, or pins can be used at the outset of the installation to hold mosses.

The combination of clay and ceramic paired as living substrate offers excellent benefits. The coefficient of thermal conductivity of terra cotta is relatively low at 0.31 watts per meter, and mosses also have a low thermal conductivity. Clay can reduce noise by 9 decibels, and mosses hold the

	Design	*Maintenance*	*Environmental Conditions*
Favorable Factors	6.7 pH Ceramic without burn-out additives Vertical forms with deeper grooves are better than horizontal with no grooves Shorter height Greater surface area Pockets Double-walled Modularity/stacking for scalability Fit to infrastructure such as pipe or frame Supplemental attachment such as mesh to hold mosses Interior and exterior area	Needs consistent water vapor 3x daily for sixty days at start for establishment Water movement Slight disturbance from insects Weekly monitoring	Winter for propagation period High humidity environment of 70% Substrate moisture Low wind Low solar exposure North-facing aspect Low elevation Proximity to wall for protection
Unfavorable Factors	Clay with 7% moss mixture Porous forms with 5% and 10% saw dust burn out Tall forms enabled salt crystals and crumbled ceramic Less texture Lack of modularity	Infrequent water with span of two weeks Too much disturbance from animals	Dry spring propagation Lower than 40% humidity High wind, High solar exposure South-facing aspect High elevation

Fig. 6.7.1. Favorable and unfavorable conditions for moss propagation and ceramic design as noted throughout the experiment.

ability to offset sound at 5000Hz, a rated Sabin rated absorption with 1.0 being perfect absorption. Both materials are near-fire resistant. Terracotta, similar in material to stoneware, can withstand 100 cycles of freeze-thawing without cracking. This low-fired clay is lighter and more adaptable than traditional brick. The permeability for water to allow air and moisture to pass is ideal for this application. Mosses are known for their ability to absorb 53% of fine dust from 1 to 10 microns within 1.5 meters. The water from that moss that is absorbed gives off a cooling effect. The combinations of mosses and clay and complementary and provoke emerging design concepts in urban environments.

Limitations

Efficiency is needed to enhance the efficacy of future design work. It is essential to design with as little material as possible in clay and moss to reduce overall extraction and costs. Increasing the production rate by having a ceramic recipe with tools to mix on a larger scale to achieve optimal viscosity and a high-performing 3D clay printer can aid in this process. Supporting the development of moss-growing farms will lessen the impact on the natural environment.

In controlled moss growing environments, incorporating a large-scale method for harvesting the tips of mosses and fragmenting them can be developed. The development of a mechanized moss application process can increase the rate of the application and scale of the overall coverage for a more significant effect. Furthermore, when substrates reach dry conditions, using a mechanized spray system connected to the internet of things to monitor substrate can mist water vapor for regular maintenance.

There are limitations within the experiment with unknown factors at the micro-scale changes place within and on the ceramic substrates. It is not clear how the moss spores are being transported near the tops of the forms. The conduction of water or microbial movement or both could be aiding in this movement.

With greater competency in identifying mosses, it would be helpful to know which mosses have propagated from the known and unknown collection of applied mosses. This could be achieved with access to a compound microscope and identification from a Bryologist. With closer proximity to the four experiments, it likelywouldhavebeenbeneficialtoincreasemisting times. The drying out of the substrate and mosses likely inhibited the Urban Farm protonema phase.

Establishing an extended time duration beyond threemonthswillrevealmoreinformationovertime.

This experiment did not test the addition of agar or binders for moss attachment; however, there is potential to try this with the fragmentation propagation method.

Fig. 6.7.2. Barnacle interfaces #9 across experiments decreasing in clay porosity and increasing in moss retention from trays left to right: 2, 3, 4. The mosses attach in a clumpy or stringy pattern.

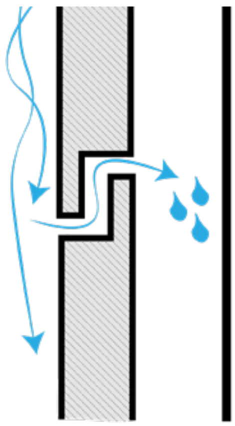


Fig. 7.0.0. Drained-Back Rainscreen showing how design of interlocking panels would reduce water on building layer.

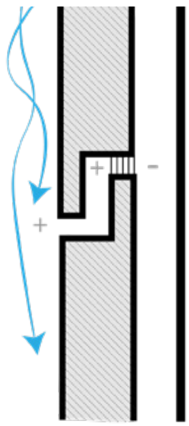


Fig. 7.0.1. Pressure-Equalized Rainscreen showing how the stop between panels creates an equal pressure zone reducing water infiltration.

Fig. 7.0.3. Iteration 2.

2. Objective: Introduction of woven texture to pattern, however, vectors were not flat to xy plane and caused the clay to peel off in an unstructured way. Too messy.

Modify: Refine woven pattern.

Fig. 7.0.2. Iteration 1.

1. Objective: Design a smooth texture with gradation of randomly plotted points.

Modify: Increase texture of the pattern.

Fig. 7.0.4. Iteration 3.

3. Objective: Reduce woven pattern and switch to every other weave.

Modify: Rework the woven pattern so that the layers compress in a stack and vary the size of the width of the loops.

7. EXPLORATORY DESIGN

7.0 RAIN SCREEN

During a design development course focusing on Grasshopper and 3D printing in clay over the winter, I expanded on my skills in both design and printing. For the duration of this course, the experiment had been set up, so some of the data from the experiment informed two different approaches in rapid prototyping.

The first approach was inspired by considering the construction of a rain screen with designing terra cotta panels that could attach to an aluminum frame system offset from the wall. Two main types of rain screens including pressure-equalized and drained-back were researched, as seen in Figure 7.0.0. This seemed like a suitable application for mosses to capture the rain on the exterior of the surface and enhance the ecology and aesthetics of the application.

Goals for designing panels included creating shelves and pockets that would increase the surface area of the outer face, capture rainwater, and create shade. The concept was that the pockets or valleys of the form would hold moss. I was interested in creating a random pattern that, through repetition, could create order.

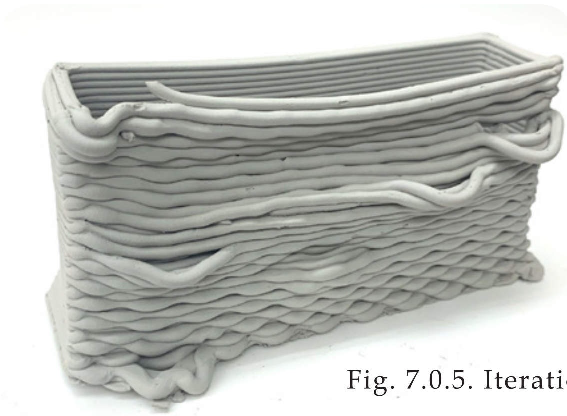


Fig. 7.0.5. Iteration 4.

3.5 Objective: Create a woven texture pattern.

Modify: More control of layer deposition.

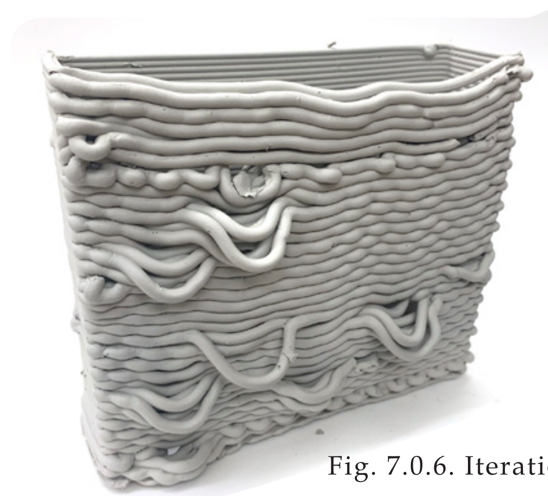


Fig. 7.0.6. Iteration 5.

4 Objective: Create a structural pattern that falls directly on top of each layer. The layers were still adjacent and the pockets are lacking.

Modify: Articulate whole surface to make more intentional and discrete grooves and pockets.

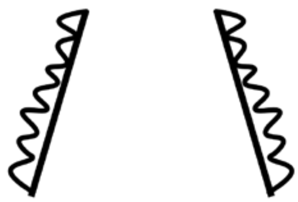


Fig. 7.1.1.

Relate form and texture back to barnacle to increase surface area and attachment for mosses.

Fig. 7.1.2.

Increase rain capture with pockets and to hold mosses.

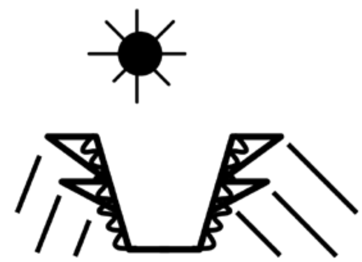


Fig. 7.1.3.

Add shade by increasing surface area with symmetrical pockets.

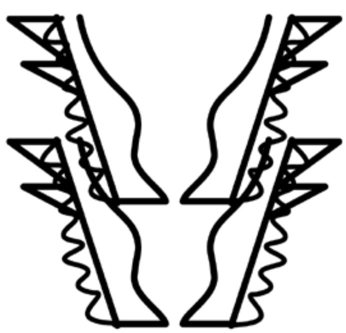


Fig. 7.1.4.

Double-wall to capture more rainwater, and retain thermal temperature. Stacking the forms increases impact.

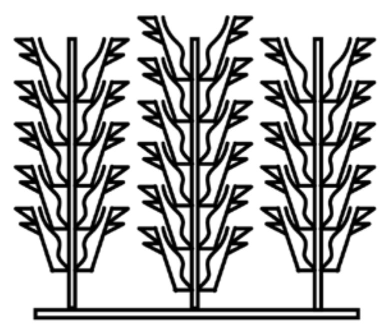


Fig. 7.1.5.

Added infrastructure to extend stacks towards double-sided screen creates even greater impact aesthetically and ecologically.

7.1 BRYOBRICK

In response to the rain screen prototypes, I realized that within the restraints of 3D printing with clay, it would be challenging to design varying heights along the bottom plane to create interlocking panels. The purpose of the rain screen design was to prevent moisture from passing through to the building and removing moisture from the panels. This concept proved incompatible in general for designing with mosses as mosses require moisture to thrive. Furthermore, the rain screen concept departed from the design work for the experiment, and I wanted to return to moving the original concepts and lessons from the experiment forward.

As a precedent for this work, I looked at Mashrabiya 2.0 3D Printed Facade and admired the evaporative cooling potential and vertical framework of a screen. The vertical structure allowed light to pass through while cooling the surrounding environment. This concept could be enhanced further by introducing mosses to aid in the evaporative cooling process and greening the urban environment.

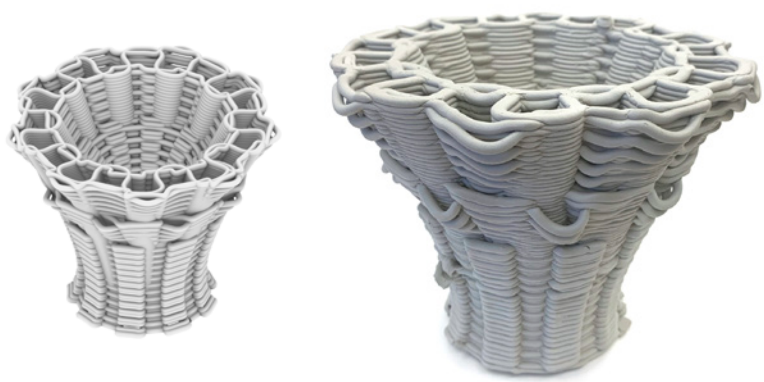
With the advanced technology of the Potterbot 7 model, I printed with more and harder clay which meant working on a larger scale, creating greater texture, and exploring overhangs with pockets. Taking the pocket concept forward from the flat panels of the rain screen, this idea was translated into a five-axis petal pocket form. The forms had various tiers of pockets, with varying distances between them. The internal and external geometries were enabled stacking.

I was interested in adapting the concept of the stacking forms to create vertical impact and arraying them in one direction to create a screen system composed of Bryobricks. This rapid prototyping process was executed over the span of a week, and I tested seven prints, making adjustments for each except for the final design. I was curious if I could achieve a cleaner print with the final design by reprinting; however, it still did not materialize with the precision I intended for the pockets.

With the translation from digital space to the printer, there was much unpredictability with variations in clay consistency, gravity, print speed, and air bubbles, as seen in Figures 7.1.6 and 7.1.11.

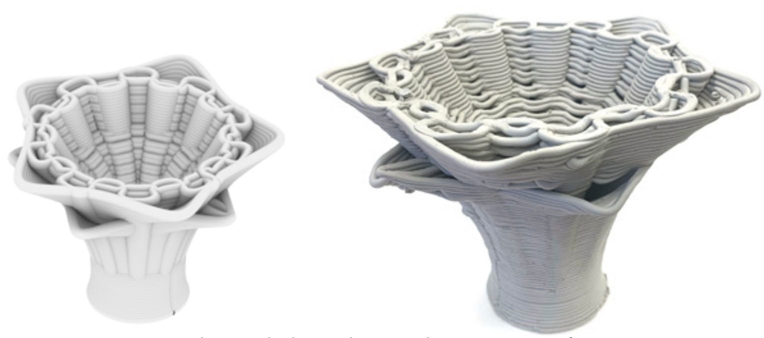
Mesh in Rhino, Axon

3D Printed in Clay



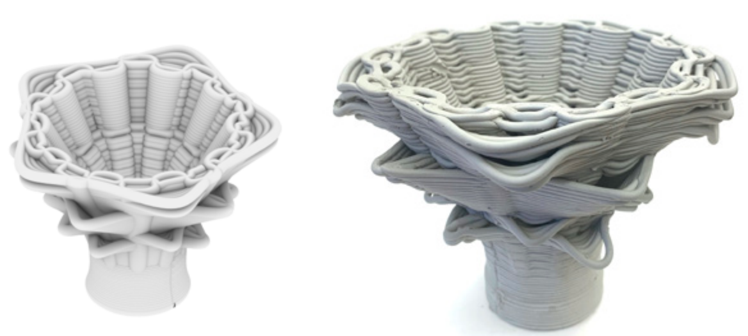
- Grooved textured stackable brick
- Created surface area and small pockets
- Weaving creates every-other compression, so the pockets are loose at the top
- Offset at 20mm
- 6mm between pocket height
- Amplitude of pocket 15mm

Fig. 7.1.6. Digital model and 3D clay print of rapid prototype 1.



- Moved base in so that it fits within stack
- Alternated texture to twist at 90 and offset at 6mm
- Decreased offset to 12mm
- Removed weave on outside wall
- Amplitude of pocket width 30mm

Fig. 7.1.7. Digital model and 3D clay print of rapid prototype 2.



- Decreased offset from inner su-face to 7mm
- Reduced amplitude to 28mm
- Played with internal wall shape
- Added symmetry to the relationship of the pockets
- Lowered branching off ratio to 2.250

Fig. 7.1.8. Digital model and 3D clay print of rapid prototype 3.

3D Printed in Clay

Mesh in Rhino, Axon

- Adjusted offset to 10mm
- Changed seed of randomly organized points that detemine pockets to 5
- Moved in inner section
- 10mm distance between pockets

Fig. 7.1.9. Digital model and 3D clay print of rapid prototype 4.

- Reduced to three tiered pockets
- Added woven texture to exterior wall
- Offset walls to 5mm
- Changed fluting division to 2.250 ratio

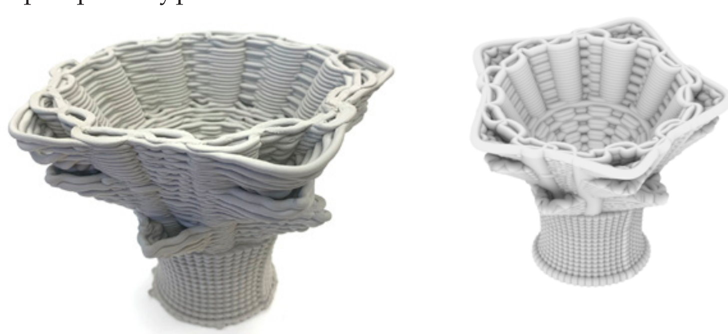


Fig. 7.1.10. Digital model and 3D clay print of rapid prototype 5.

- Returned to two tiers of pockets
- Elevated branching area to 2.2
- Changed silhouette of form
- Pushed inner arch out for more support
- Two prints with different results because of varying clay consistency

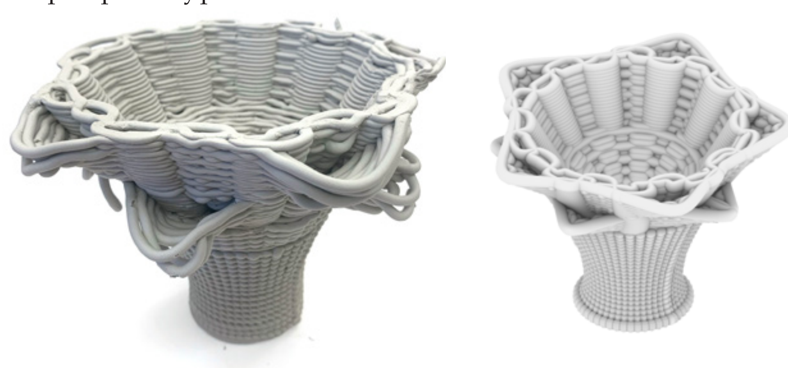


Fig. 7.1.11. Digital model and 3D clay print of rapid prototype 6.

- Returned to two tiers of pockets
- Elevated branching area to 2.2
- Changed silhouette of form
- Pushed inner arch out for more support
- Two prints with different results because of varying clay consistency

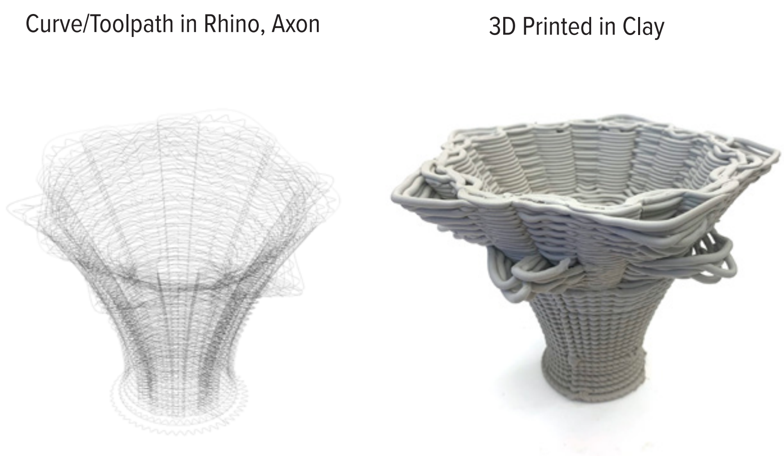


Fig. 7.1.12. Digital tool path and 3D clay print of rapid prototype 6.1.

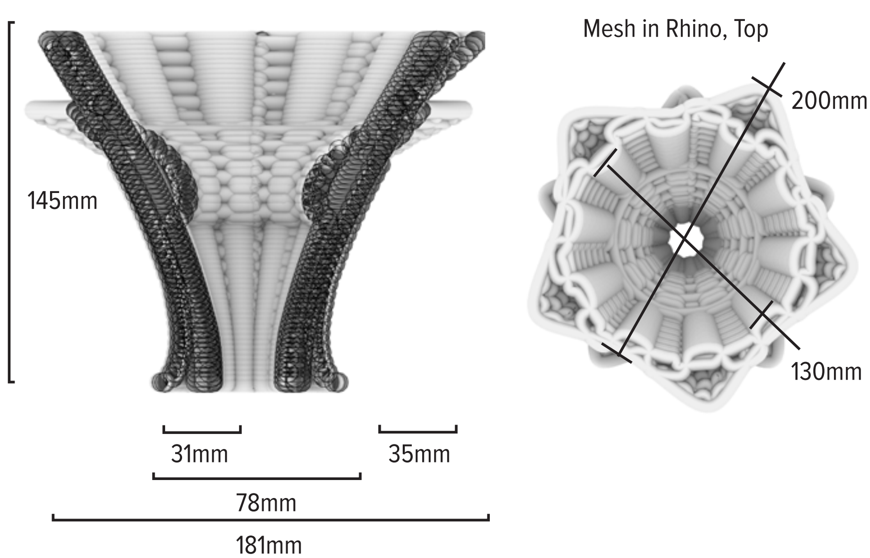


Fig. 7.1.13 Dimensions of prototype 6.1.

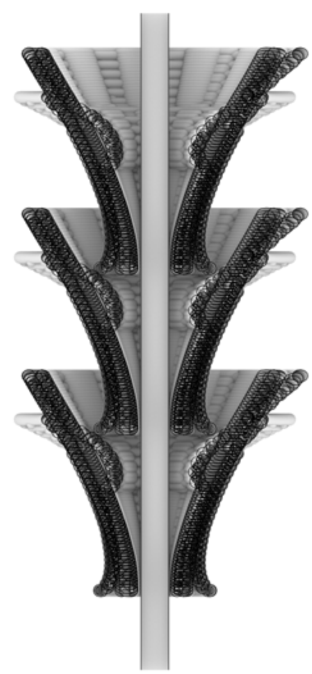


Fig. 7.1.14. Stacking fit along pipe

1. 2. 3. 4. 5. 6.

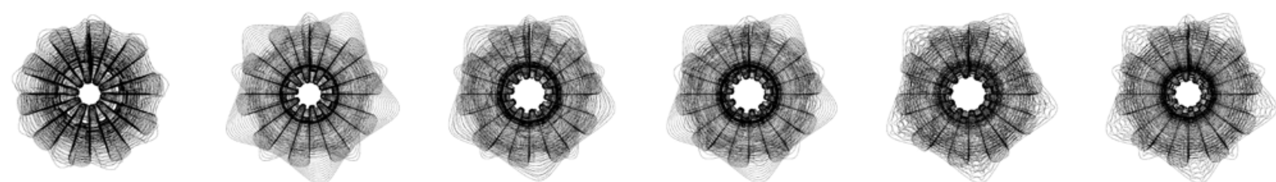


Fig. 7.1.15. Top, Toolpath.

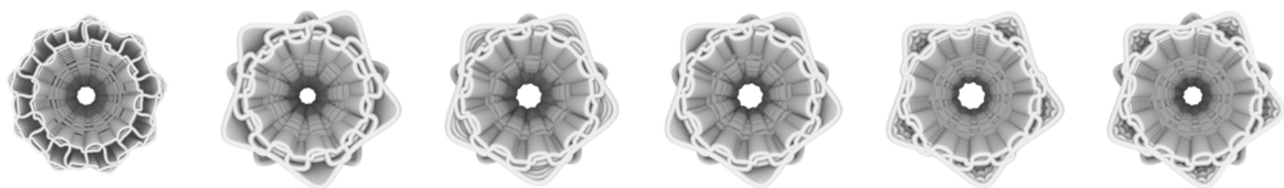


Fig. 7.1.16. Top, Piped Mesh.

Fig. 7.1.17. Elevation, Piped Mesh.

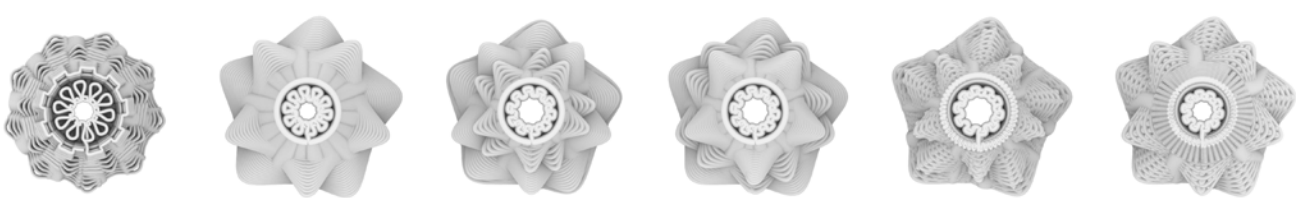


Fig. 7.1.18. Bottom, Piped Mesh.

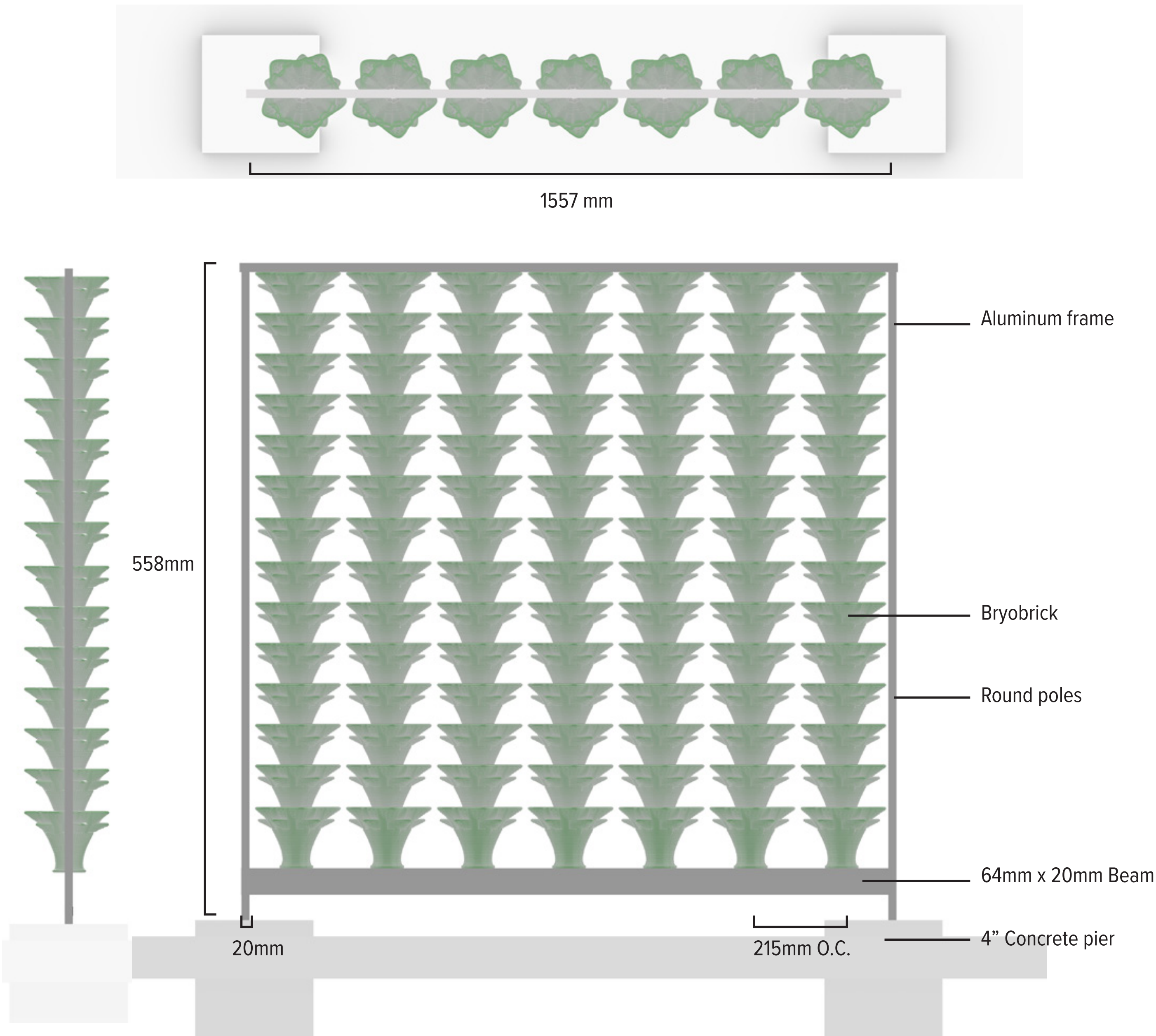


Fig. 7.1.19. Screen Section Elevation.

Meta-analysis

Purpose

The purpose for the ideation of a two-sided screen with bryobricks serves to function as a modular and responsive tool that could be implemented on a greater scale or with flexibility. I was interested in taking the ideas forward that I had learned from the experiment and to consider a structure that would do well with exposure to the rain.

Implication

These exercises in producing a bryobrick supported by a pipe are concepts that leave room for further application and development. This type of structure is not common in the built environment and can create shade, aesthetic interest and assist in evaporative cooling. The segment shown to the left can be replicated and adjoined to have a greater impact. This work serves to inspire and work with the local ecology to create enhanced performance in suitable environments.

Approach

By identifying design concepts that I wished to bring forward, I needed to apply them by testing the material output of using the Potterbot 3D clay printer. With assistance in generating the script in Grasshopper, I developed different iterations only after a print to learn how to modify the print. This was an abductive method of creating and then responding to the created form.

Limitation

While I learned quite a bit through developing seven iterations for the final bryobead, I realized that the printer was still not able to successfully print the work that I designed. With further refinement of the design, the output would be more substantial. The limitation in this design is that it was not produced as a prototype or tested, so it is difficult to understand how it would assemble and function for creating a positive impact.

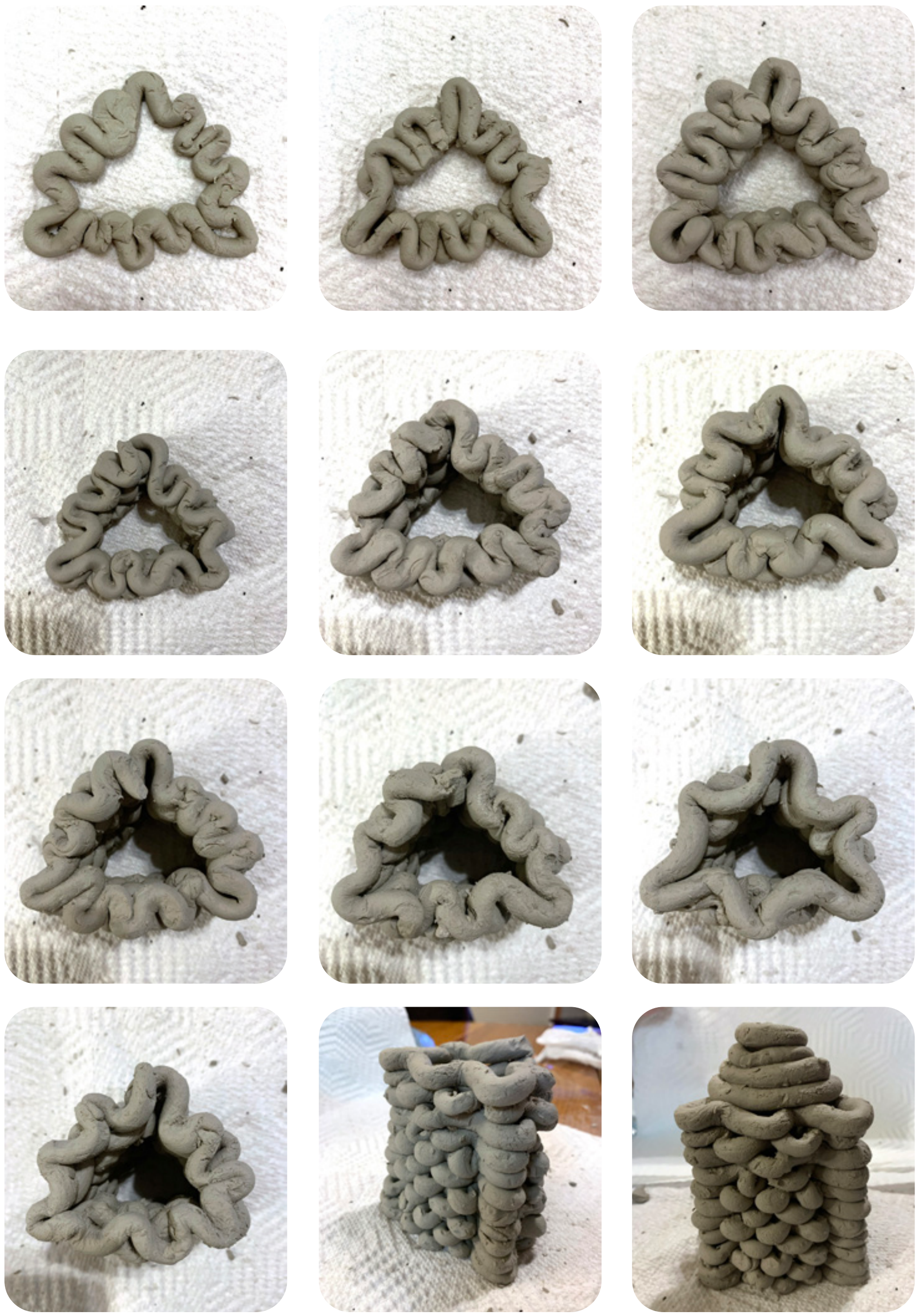


Fig. 7.2.1. Coil building process.

7.2 PHOTOGRAMMETRY TRANSLATION

This exercise explores translating the forms generated for the experiment to create a new geometry merging two methods; the ancient art of coil-building with the hands and the latest technology of photogrammetry realized through 3D printing in clay.

This process builds on the age-old technique of coil-building, stacking layers of coils and stitching them together to build a form independent of other tools. The coil building process requires only the hand and is an additive process that can take on exciting forms. By starting with clay to coil build, it involves drawing with the output material.

This process is different from the design development for the experiment, as I started by drawing with a pencil on paper to identify form attributes. This design of the work builds on the forms generated by the experiment, as I aimed to translate the weaving pattern created in Grasshopper to make the textured surface.

The coil building process is similar to 3D printing in that 3D printing involves deposition modeling whereby the form is created layer by stacked layer. Without the hand being directly involved in the 3D printing process, this exercise involves a haptic experience of emulating the printer to arrive at a design.

The aim of this design has similar goals to the previous design work of the Master's Project in creating a stackable, woven and textured clay form and printing the work through the 3D clay printer. The coil-built work is similar to the beaded work that could potentially stack.

Photogrammetry is the process of taking many photographs to build a mesh from points generated by photographic images, as seen in Figure 7.2.1. I used Meshroom to import the photos to generate the mesh and texture, as seen in Figure 7.2.2-7.2.4. From Meshroom, I exported the mesh into Rhino to trim to the base and to make an stl. file to translate to gcode, as seen in Figure 7.2.5. Using Simplify3D, I translated the mesh to gcode.

The output of the original form was reduced in scale to increase the success of the output. Notice

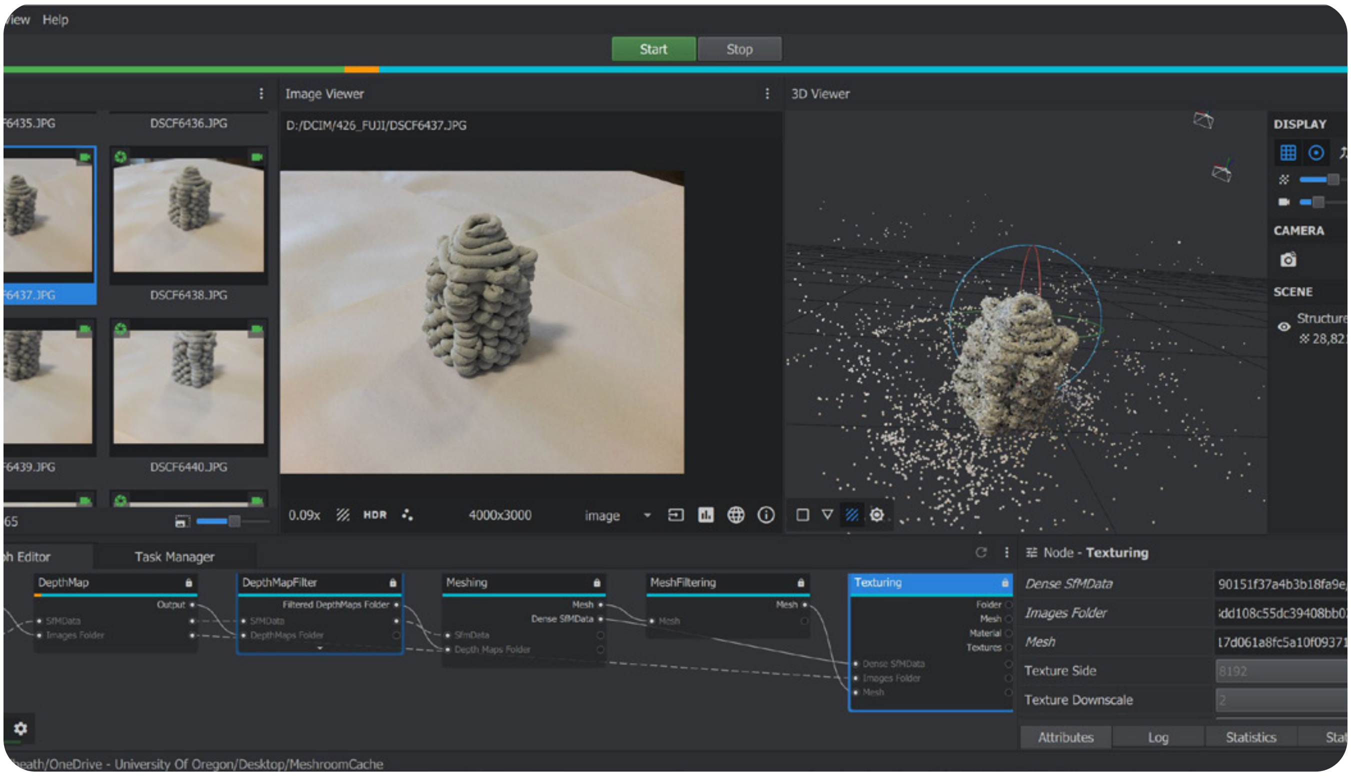


Fig. 7.2.2. Mesh-Making process in Meshroom.

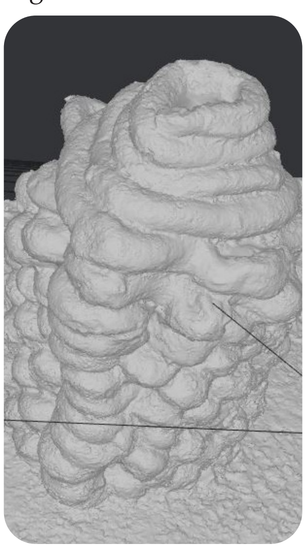


Fig. 7.2.3. Mesh, Meshroom.

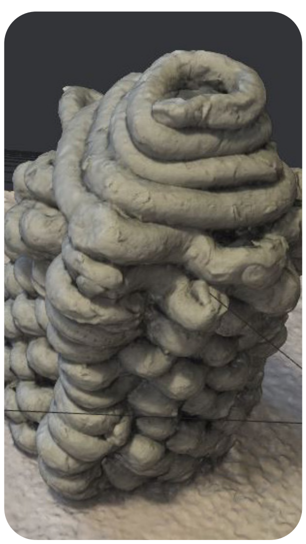


Fig. 7.2.4. Texture, Meshroom.

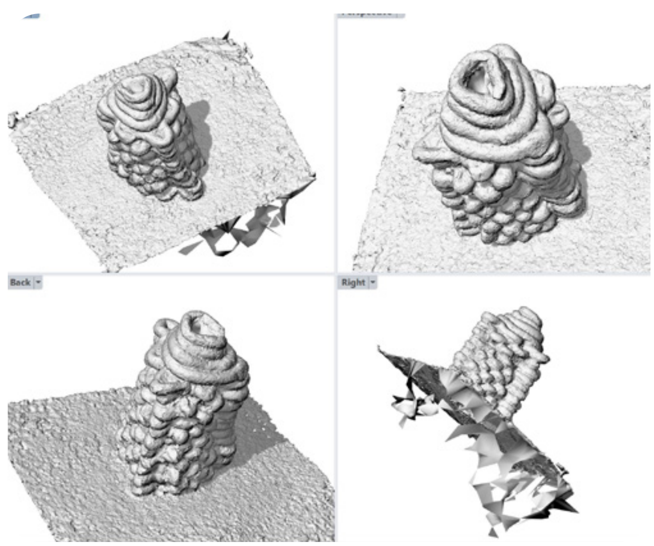


Fig. 7.2.5. Rhino to trim away extra mesh and slice.

that the coil thickness is very thick in the original form and very thin in the 3D printed structure. The vantage points from the final print show the different faces of the translated mesh and nod to the photogrammetry process. Perhaps these steps could be emulated again by taking photographs of the 3D printed output to generate new points to see how the 3D clay printer could again translate this form. There are limitless opportunities by translating existing geometry and designing geometry to enhance the built environment processes.

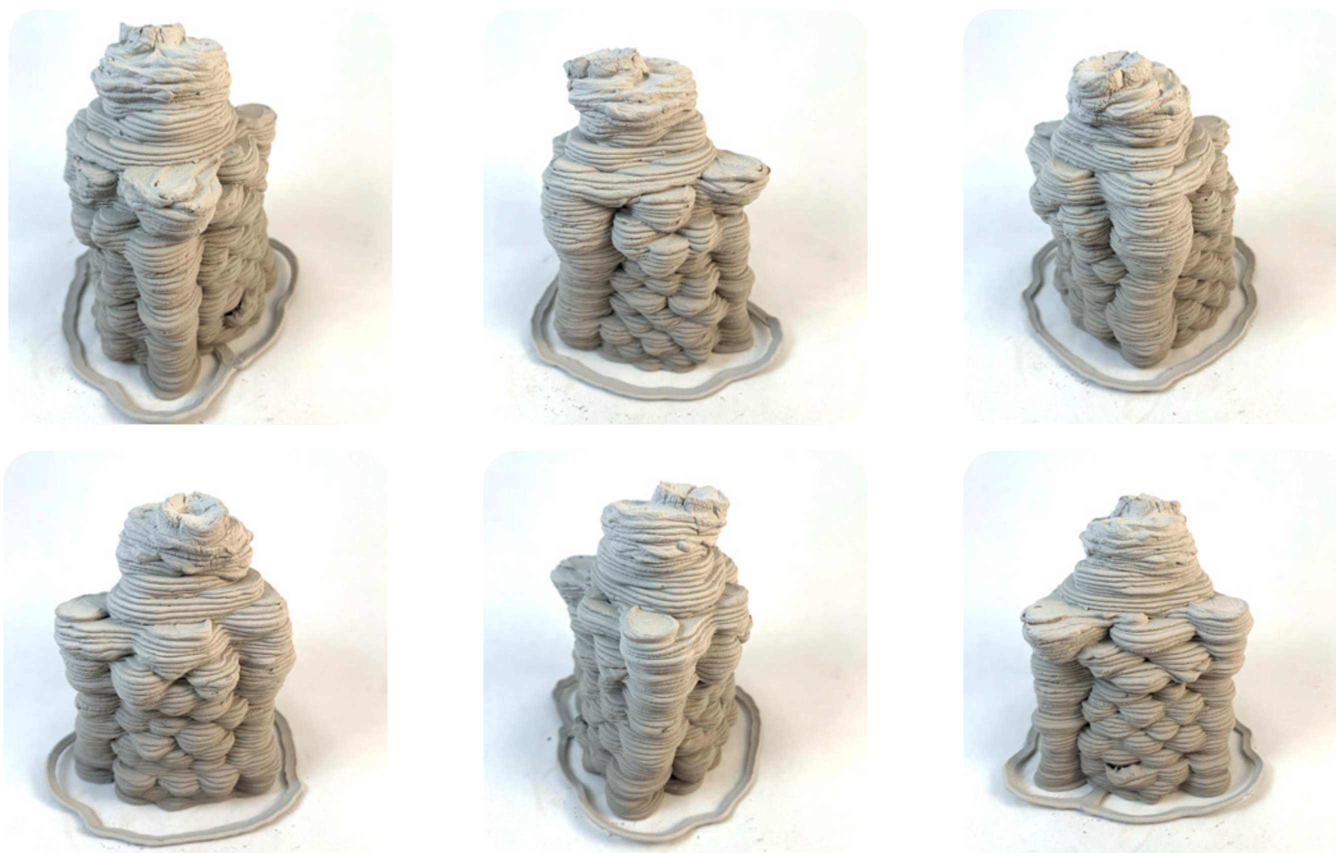


Fig. 7.2.6. 3D Print of Coil-built Bryobrick.

Steps

Fig. 7.3.0.
1 step
.5line
6ft
10 vol.

Fig. 7.3.1.
3 steps
.5line
6ft
10 vol.

Fig. 7.3.2.
Anemone
in final design.

Point on Line

Fig. 7.3.3.
5 steps
.3line
6ft
10 vol.

Fig. 7.3.4.
5 steps
.4line
6ft
10 vol.

Fig. 7.3.5.
5 steps
.5line
6ft
10 vol.

Spacing Feet

Fig. 7.3.6.
5 steps
.5line
4ft
10 vol.

Fig. 7.3.7.
5 steps
.5line
5ft
10 vol.

Fig. 7.3.8.
Rotated
5 steps
.5line
6ft
10 vol.

7.3 ANEMONE

The repetition of the geometry at different scales can add value to the relationship of the space and offer health benefits through its visual rhythm. This exercise involved using the anemone plug-in within Grasshopper. The columnar geometry was rapidly created from a pentagon curve by shifting applied parameters such as the number of steps, a point on curve, z height, and volume. The advantage of using Anemone enables the creation of loops for information to build on itself.

The goal for this work was to make geometry that could be printable with a 3D clay printer, which meant creating forms with greater slope. I explored varying the steps, a point on curve, and z heights to find an interesting form. The form I landed on was with 5 steps, .5 on the line, 6ft height between intervals, and 10 ft. in volume. The .5 of the line meant that the rotation took place halfway from each facet as the form built up. I was interested in what the form looked like rotated 180 along the xy axis during the patterning sequences of the base, capital, and shaft. This form in the applied design is shown situated upright and upside down and was scaled by .5 to make the geometry fit in the plant bed space near the vine maples.

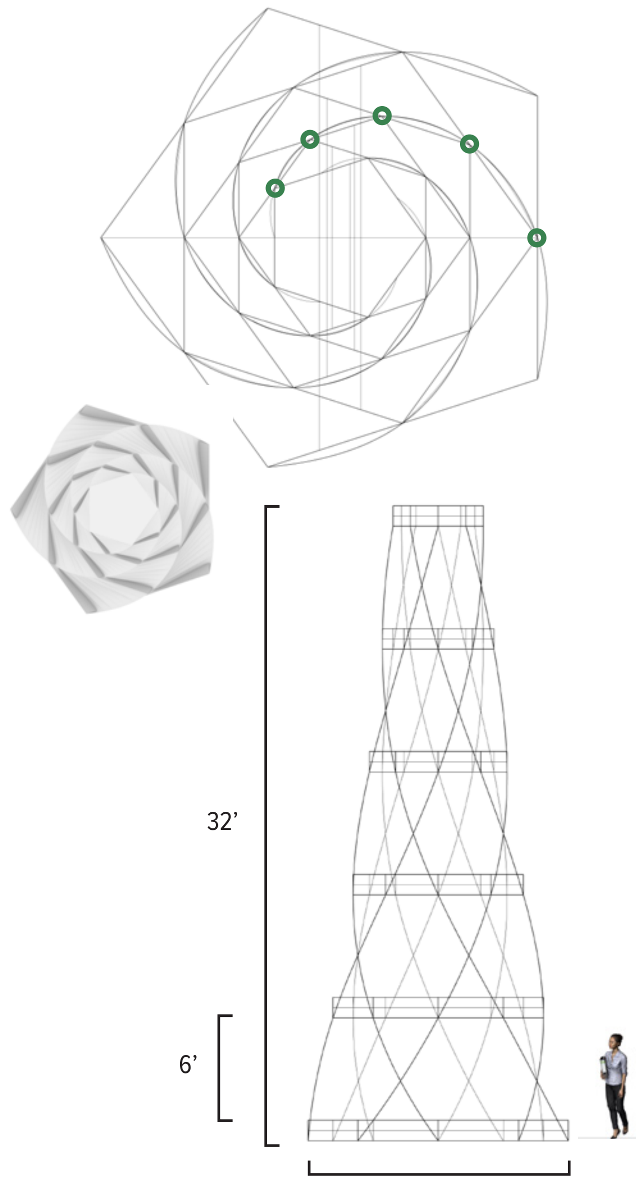


Fig. 7.3.9. Fractal geometry, 5 point, 5 steps .5line, 6ft, 10 vol.

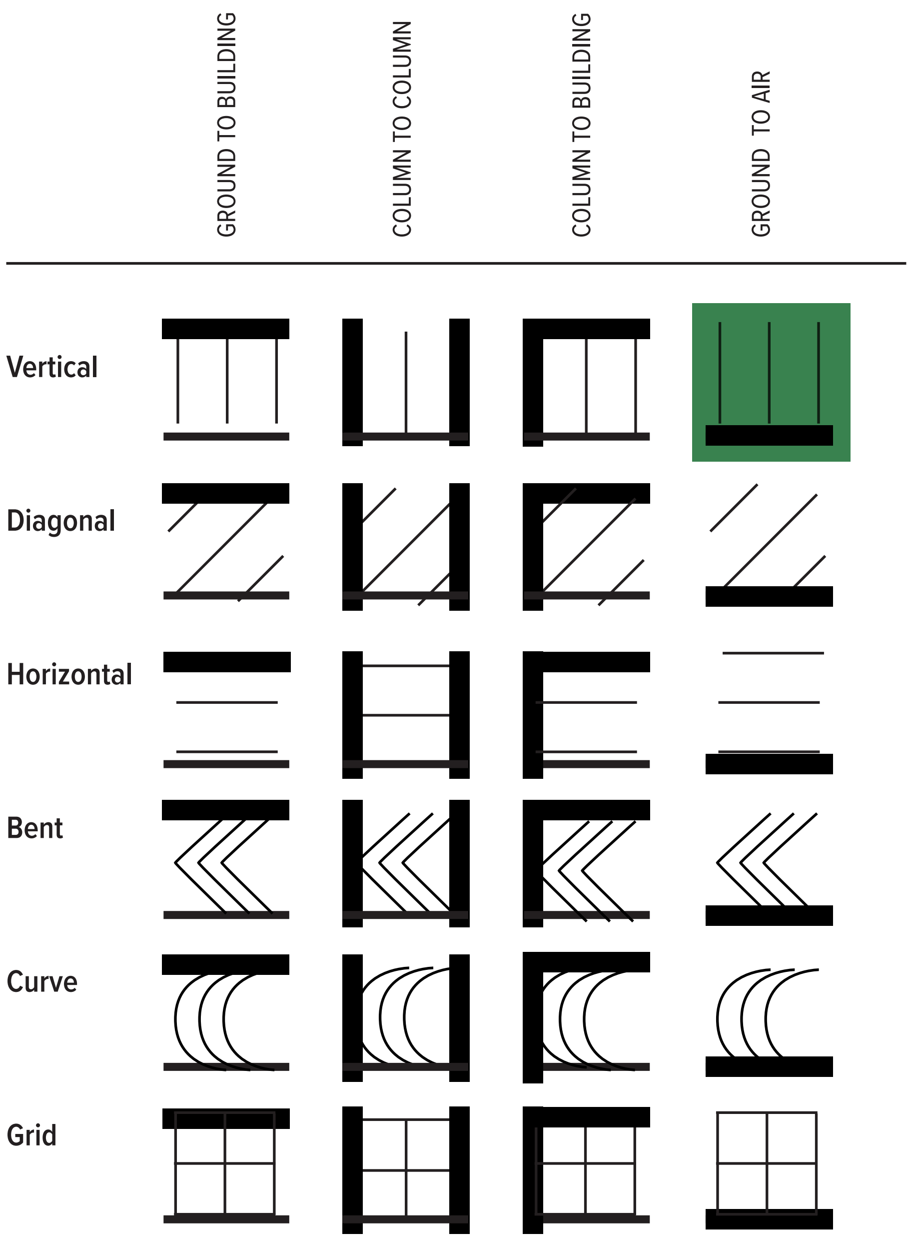


Fig. 8.0.1. Typological exploration on how vertical system could connect to existing infrastructure.

8. FINAL DESIGN: BRYOBEAD MATRIX

8.0 BACKGROUND

Lessons learned throughout the Master's Project have been incorporated into the final speculative design. From each phase of the project, from research to the experiment, to analysis, this work reflects on previously generated work through abductive methods. In response to the rapid prototyping work, I aimed to advance the bryobrick screen system concept for a specific site and redefine the typology in response to the site. I chose the Lawrence Hall courtyard at the University of Oregon as the site for this final work as it is near the location where the research and moss observations began. The Lawrence Hall courtyard is a contained, flexible space similar to other suitable urban typologies like alleyways or within the northern shadow of buildings. The shaded courtyard offers exciting potential for designing with mosses. If the design were to be materialized, the work would demonstrate design and experiment in an academic context, serving as an exciting platform for further discussion and development.

When approaching how to move the bryobrick screen system forward, I considered the connective natural and built structures that define the courtyard area; from ground to building, from column to column, from column to building, and ground to air, as seen in Figure 8.0.1. While I worked with straight pipes for the screen system, I considered the possibility of working with curves, diagonal lines, bent forms, and a grid. As a beginning digital designer, I thought that working with basic geometries such as the straight pipe would be easier to design with and advocate for in a structural context. Near the main entrances of buildings, plantings, such as foregroves, can have an impressive, transitional, and welcoming effect. To apply these ideas, I explored creating a matrix to expand on the screen system. This approach allows for creating rooms and places to wander through in the courtyard setting. Creating a collection of independent columns also allows people to interact closely with the work and view it from above.

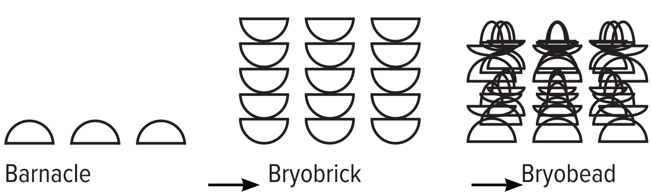


Fig. 8.0.2. Concept diagram of Ground to Screen to Matrix.

Research

- Mosses
- Ceramic
- Digital Design
- 3D Printing
- Bio-Design
- Architecture
- Landscape
- Product Design
- Experiment

Case Studies

- Mashrabiya 2.0
- Beads as evaporative cooling
- Biota
- Cementitious material as substrate for mosses
- Gagneux
- Conveying water through ceramic design

Technology

- Grasshopper
- Plug-ins
- Gcode
- Cerambot
- Rhino
- Twin Motion

Typology

- Barnacle Test Interfaces, horizontal dimension
- Bryobrick Screen horizontal and vertical dimen-sion
- Expanding dimension from 1D, 2D to 3D Bryobead Matrix
- Vertical, hori-zontal, diagonal forms piped forms explored (chose vertical)
- Stacking, patterned, piped support

Speculative Design

- Exploring new typology of column matrix and expanding potential of courtyard space consid-ering existing conditions at Lawrence Hall at UO
- Adaptable design to other urban locations
- Installation accessible to academic community for response
- Local consid-eration in a familiar and accessible environment

time →

Fig. 8.1.0. Methodology showing abuctive methods from associative methods for relating phases throughout Master's Project.

8.1 DESIGN FRAMEWORK: BRYOBEAD MATRIX

Experiment

Provide irrigation and direct exposure to precipitation

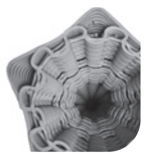
Increase shade

Increase surface area

Visibility for maintenance

Applied moss application with hands and sustainable harvesting with only tops of mosses

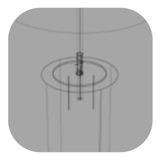
Rapid Prototyping



Development of 3 forms (base, capital, shaft) to create maximum variability for piped structure

Amplitude of grooves, offset form, 5-point axes, and conical forms carried forward from rapid prototyping of barnacle and bryobrick

Composition



Patterned 3 final sequences of forms to find the most variation and aesthetic interest (chose the third)

Bryobeads are stacked on perforated stainless steel pipe with aluminum irrigation pipe zigzagging across the tops for hydration and stability of pipes.

Base is secured by 12” deep concrete piling and with permeable moss cushion and rock at ground level

Exploring scale of form of actual size of print for bryobeads

Analysis

Computational, Grasshopper

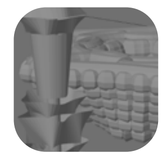
Explored column spacing (4,5,6’) on center by looking at arrangements that received less than 3.5 hours of sunlight per day

Chose 5’ on center for maximum functionality using sunlight hours analysis

Column seed arrangement created rooms within matrix

Anemone form-building as an alternative digital form-making tool.

Scale



Bryobeads at actual scale in installation with applied moss

landscape furniture, fountain, treelight scaled at 13.5X, 15X, 30X respectively

Fig. 8.1.1. Base, capital and shaft components shown in clay in top, elevation, and perspective views.

FINAL BRYOBEAD FORMS

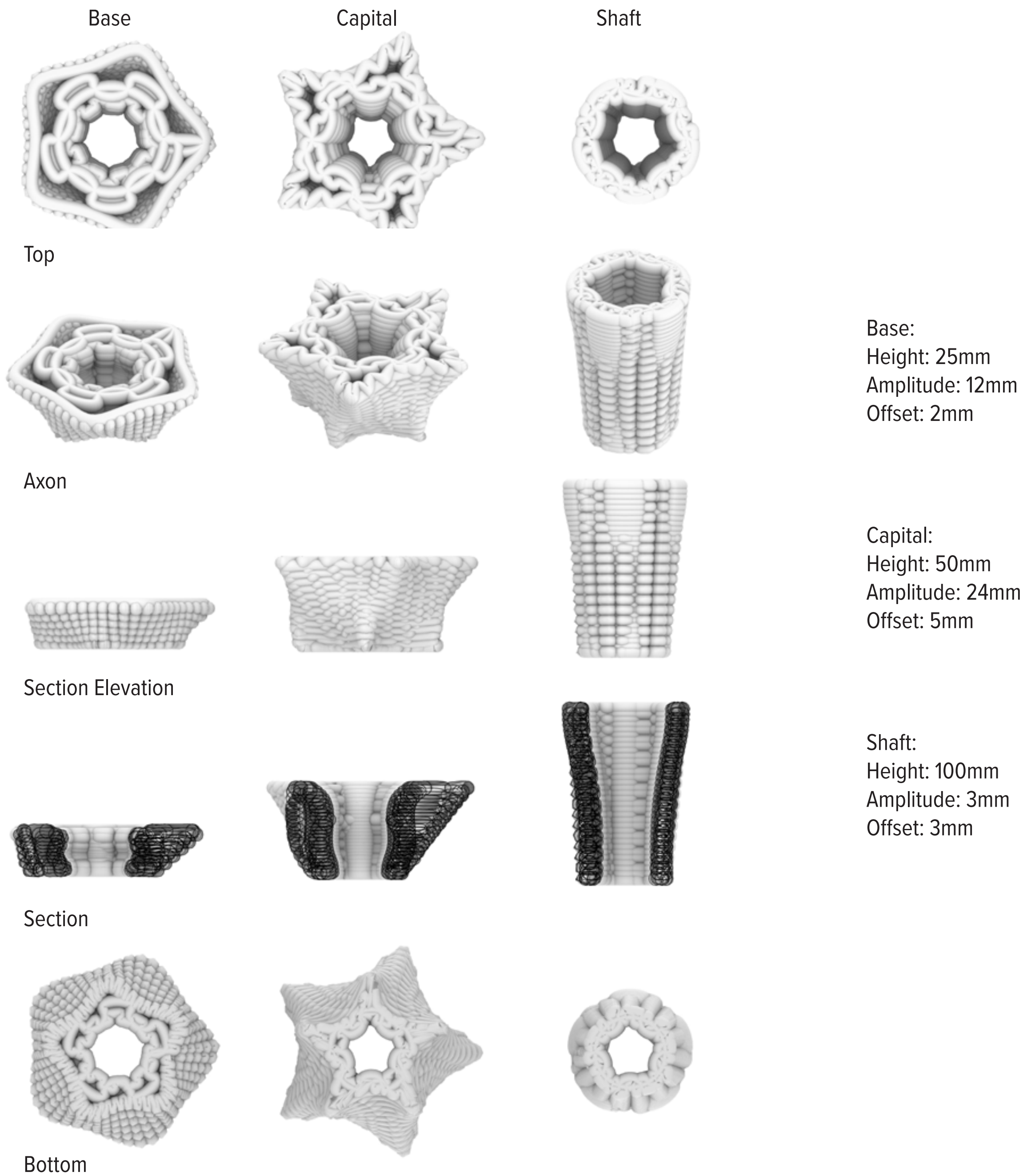


Fig. 8.1.2. Base, capital and shaft components shown in digital top, axon, elevation, section, and bottom views.

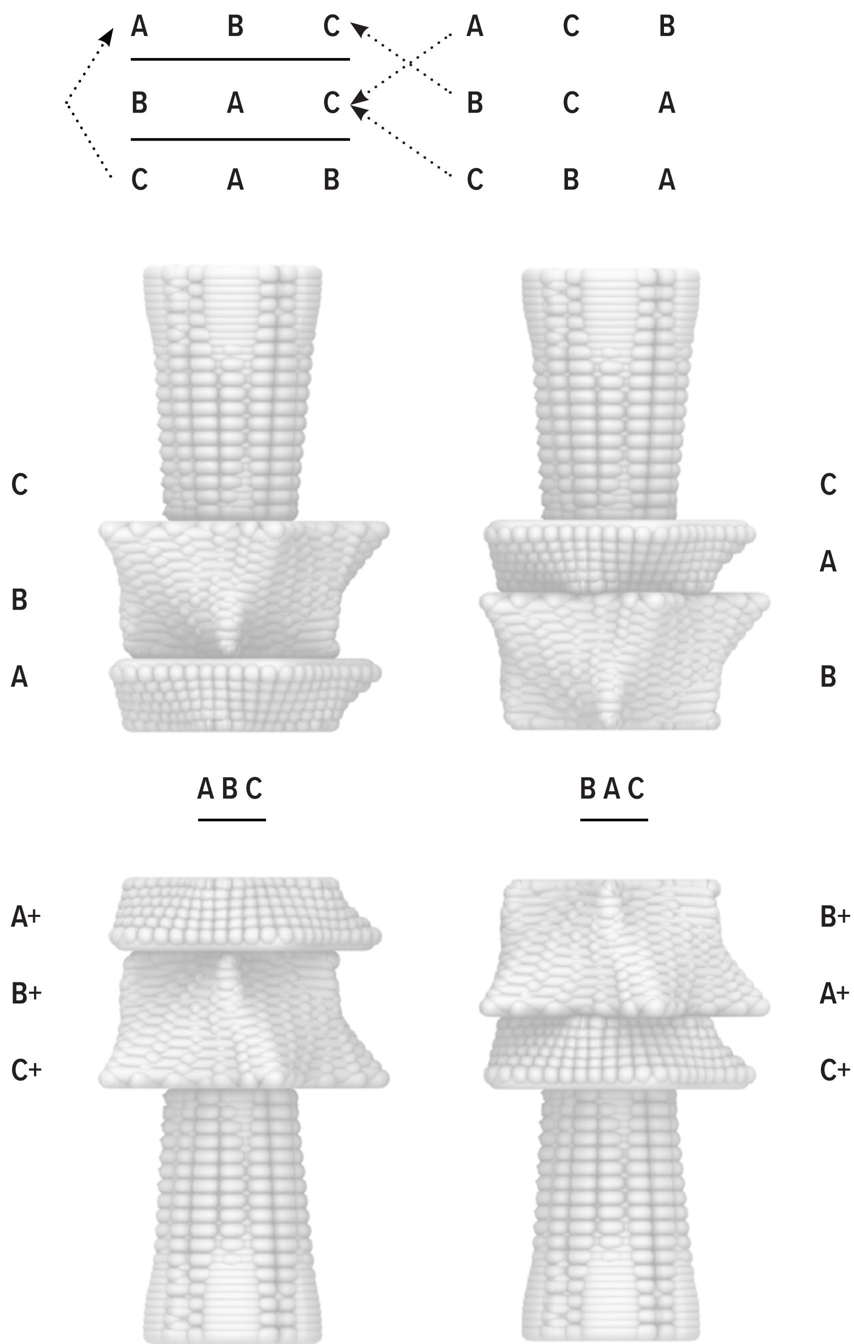


Fig. 8.2.0. Patterning Logic of base, capital and shaft.

8.2 PATTERNING

Expanding on the design of the rapidly prototype bryobrick for the screen system, I was interested in creating three types of bryobeads that would stack on a stainless steel pipe. The varying patterning of small forms would increase surface area and create variable slopes that would cast shade and receive water. The design was informed in part due to the limited technology to which I had access. I lost access to the Potterbot printer for this final rapid prototyping work and returned to working with the smaller Cerambot printer. This shift towards the smaller scale required working on a smaller scale, with wetter clay, and the limitation of exploring simpler geometries with less overhang.

For the final phase of rapid prototyping, I chose geometry with five axes and a 32 percent rotation to create more variation, stability, and surface area. The three types of forms are called the base, shaft, and capital, borrowing language from the structure of a column. The three types hold the possibility to be positioned right-side-up and upside down. The base is 25mm in height with a texture amplitude of 12mm and offset by 2mm. The capital is 50mm in height with a texture amplitude of 24mm and offset by 5mm. The shaft is 100mm in height with a texture amplitude of 3mm and offset by 3mm.

Once the forms were defined, I organized the three forms to create patterns by simply connecting letters to each form: a to base, b to capital, and c to shaft. By arranging the three letters, I found that two patterns were able to be uniquely established, as seen in Figure 8.2.1. The forms were mirrored across the XY axis to create more possibilities. The forms with the phlange near the base were given a plus near the letter to denote the orientation. The third step involved arranging three letters with all possible combinations to determine more complex geometries of fifteen options for each segment, as seen in Figure 8.2.2. The segments were then rotated to create three-column options.

From the three columns, patterns were developed. The first was simple, with consecutive geometries stacked next to one another, and the second and third were more diverse. I selected the third pattern and removed two shaft pieces to shorten the span of the pattern to create more complexity. The patterned piped columns are composed of 4.5 sequences of the pattern and stand 25’ tall off the ground to match the first floor of Lawrence Hall, where the surrounding columns connect to the building.

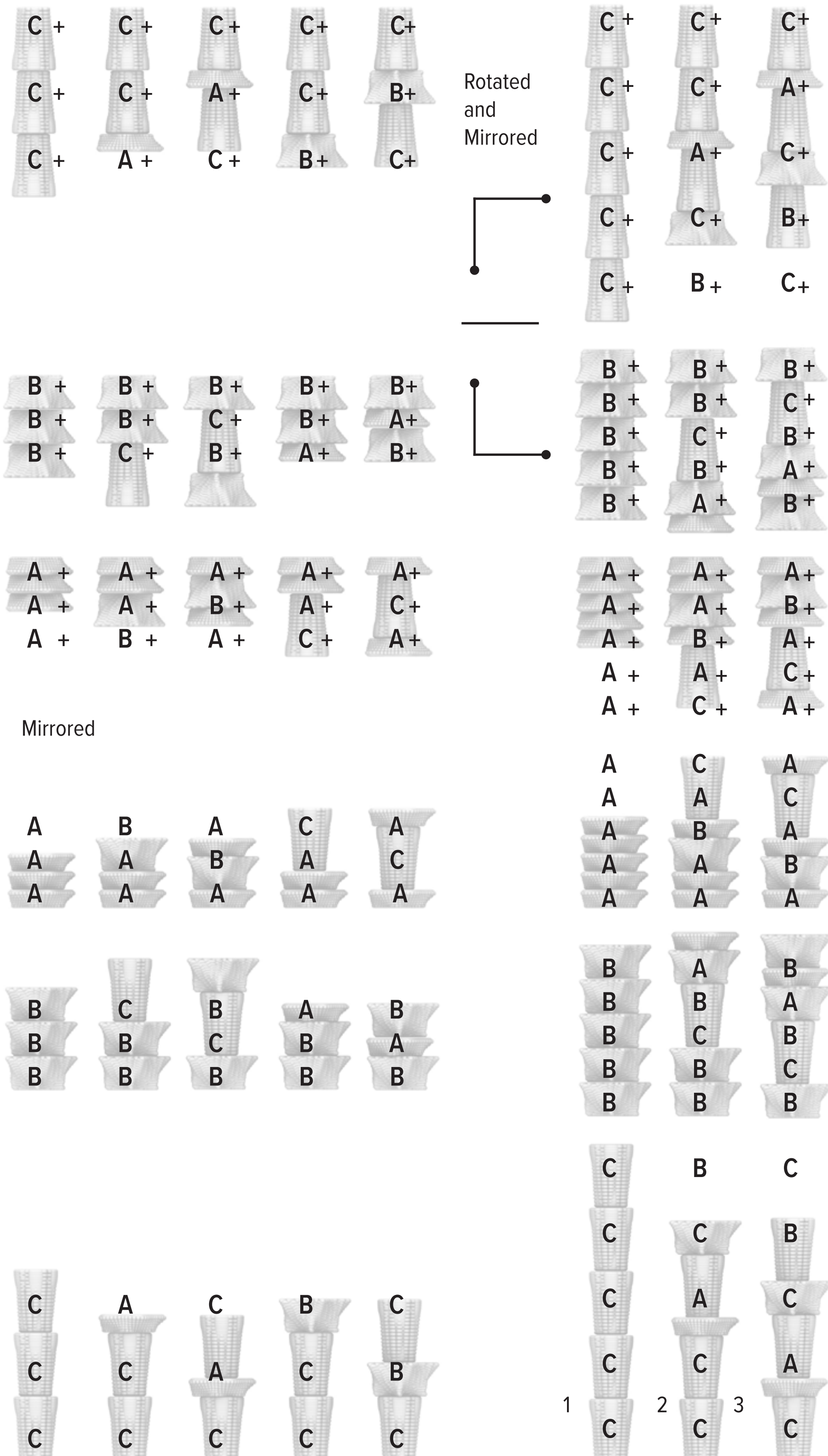


Fig. 8.2.1. Unique variations of combinations of three.

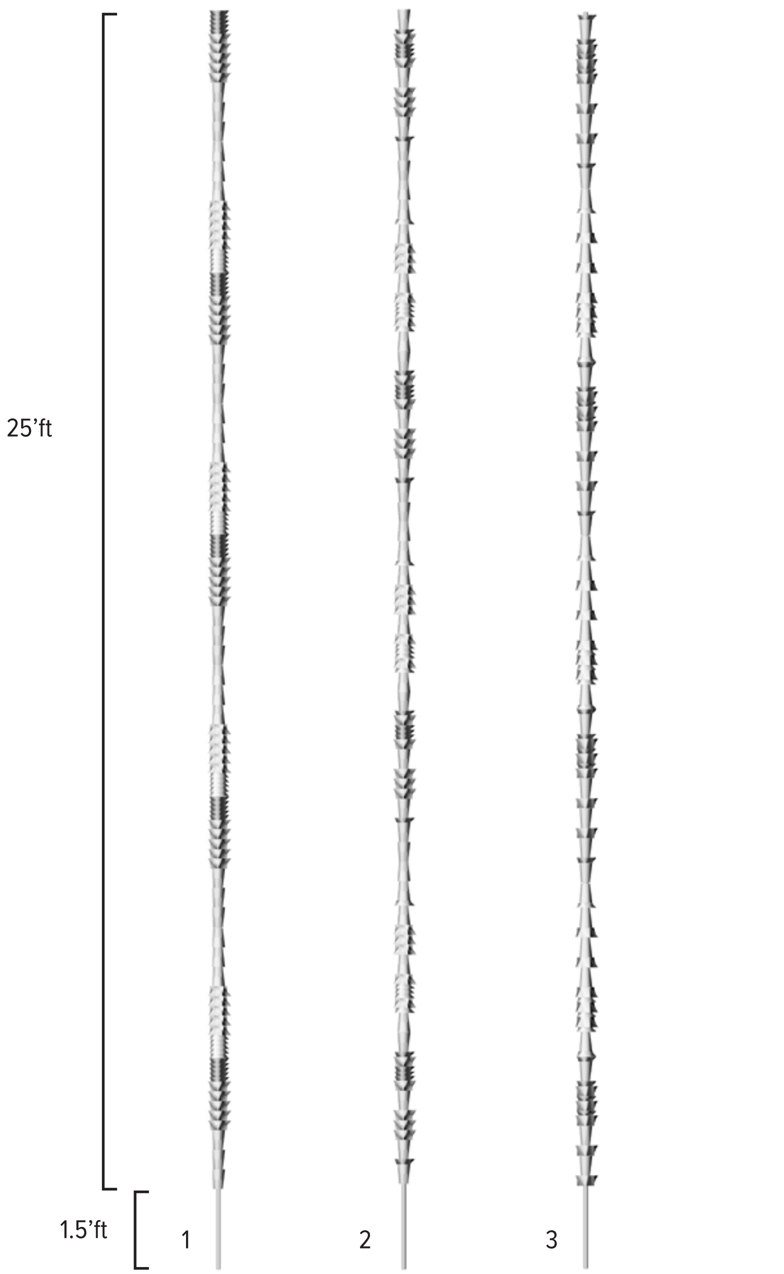


Fig. 8.2.2. Three patterns established along a column.

Fig. 8.2.3. Spacing considerations for a column.

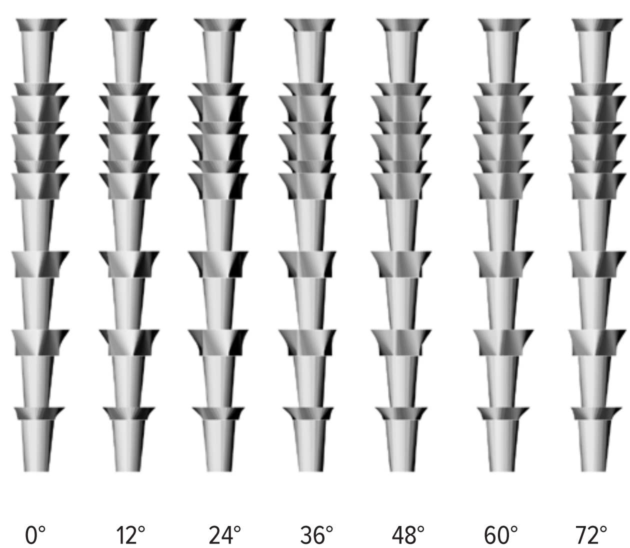


Fig. 8.2.4. Rotational considerations.

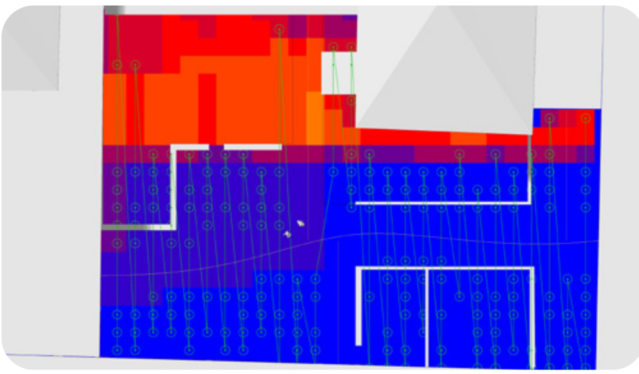


Fig. 8.3.1. 4′ spacing, 70 number, 3 seed - sunlight hour study.

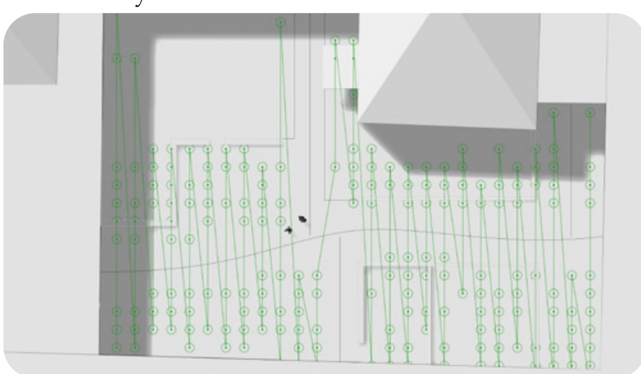


Fig. 8.3.2. 4′ spacing, 70 number, 3 seed - top view.

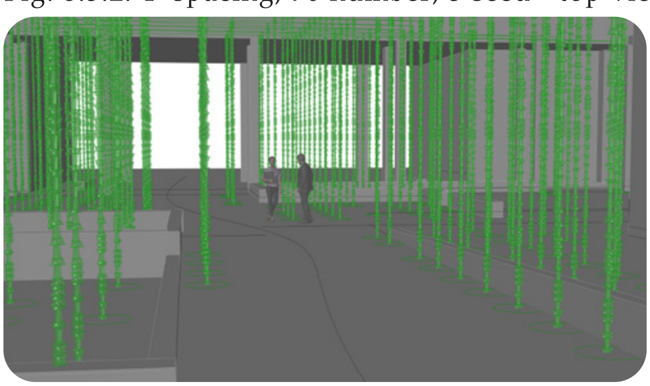


Fig. 8.3.3. 4′ spacing, 70 number, 3 seed - looking west.

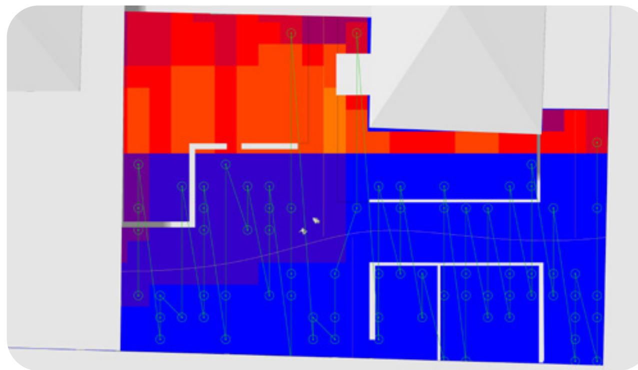


Fig. 8.3.4. 5′ spacing, 70 number, 3 seed - sunlight hour study.

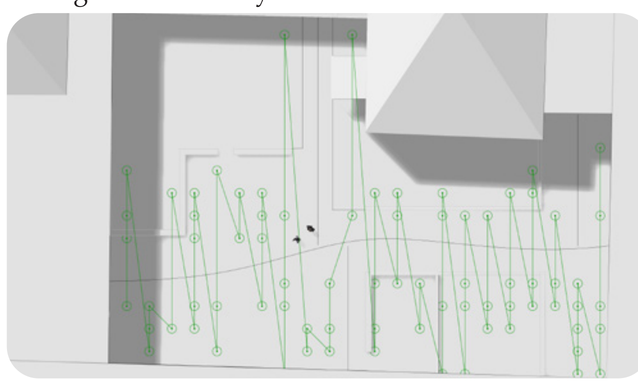


Fig. 8.3.5. 5′ spacing, 70 number, 3 seed - top view.

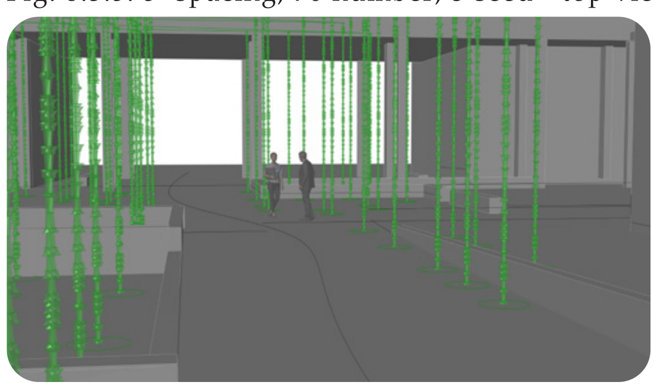


Fig. 8.3.6. 5′ spacing, 70 number, 3 seed - looking west.

8.3 COURTYARD ANALYSIS

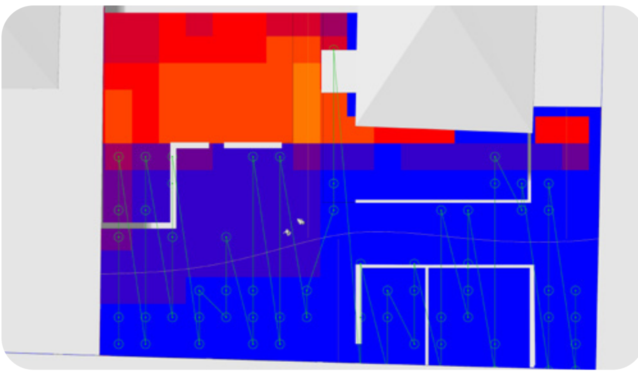


Fig. 8.3.7. 6′ spacing, 70 number, 3 seed - sunlight hour study.

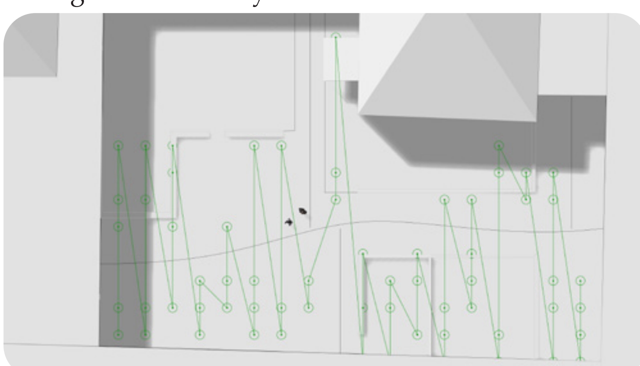


Fig. 8.3.8. 6′ spacing, 70 number, 3 seed - top view.

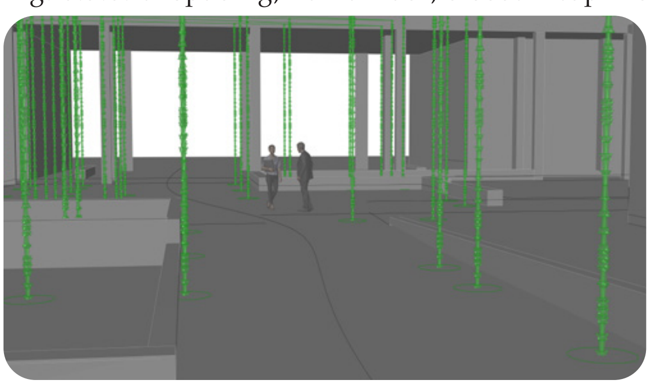


Fig. 8.3.9. 6′ spacing, 70 number, 3 seed - looking west.

After analyzing each of the experiment sites' solar hours and solar radiation, it was important to integrate this data to inform the final speculative design work. By connecting the geometry of the patterned bryobead pipes and the ground plane in Grasshopper, I was able to determine which places in the courtyard received 3.5 hours of sunlight per day. This information was highlighted in warm tones. By culling the areas that received more than 3.5 hours of sunlight a day, Grasshopper distributed the bryobead piped daylight to the shadier areas. The geometry distributed included the bryobead piped column with the third pattern, a 1′ radius circle at the ground level for holding moss and a rock, and a connecting irrigation zig zag pipe across the courtyard.

I first explored the spacing of the columns while considering the circular base of moss and rock near the base. I started with 4,′ 5,′ and 6′ spacing by playing with different seeds (random organization), and numbers of poles. I landed on the 5′ spacing because it would be easiest for most people to navigate between the columns, including a narrow wheelchair. By looking at the perspective and top views, I understood the arrangement in relation to people to make a sound.

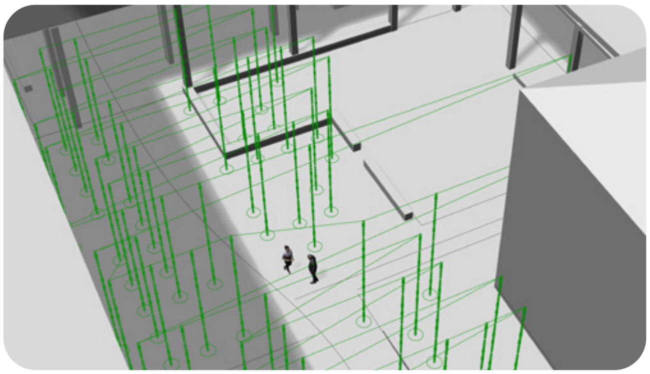


Fig. 8.3.10. 5′ spacing, 80 number, 3 seed - perspective.

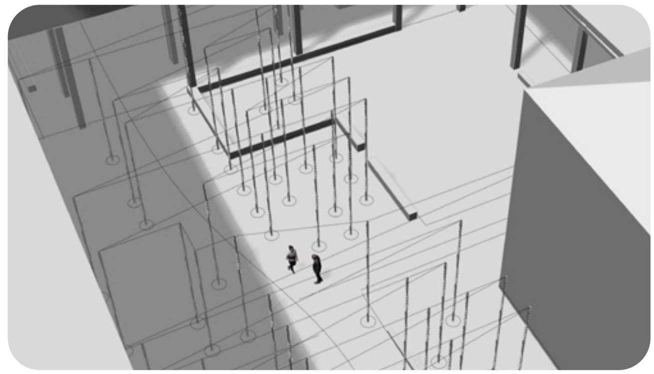


Fig. 8.3.13. 5′ spacing, 120 number, 1 seed - perspective.

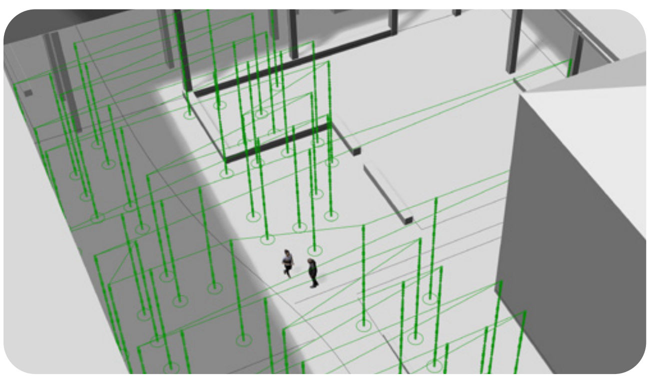


Fig. 8.3.11. 5′ spacing, 100 number, 3 seed - perspective.

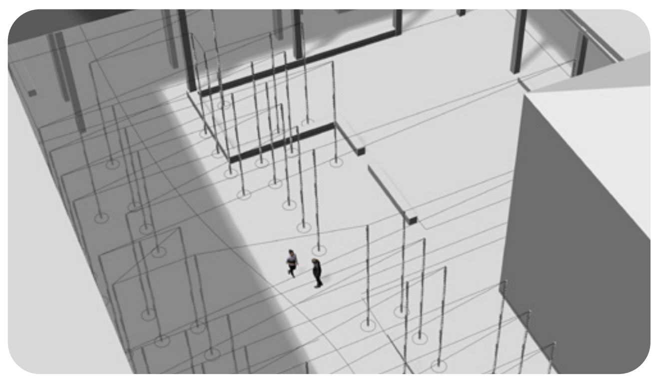


Fig. 8.3.14. 5′ spacing, 120 number, 2 seed - perspective.

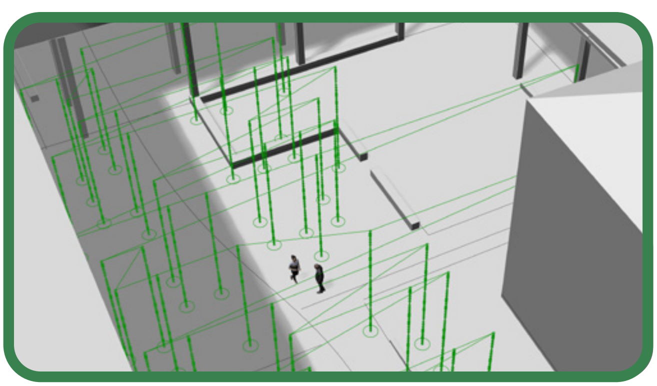


Fig. 8.3.12. 5′ spacing, 120 number, 3 seed - perspective.

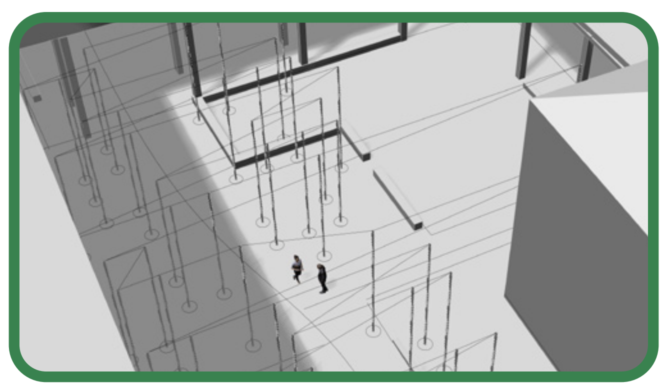


Fig. 8.3.15. 5′ spacing, 120 number, 3 seed - perspective.

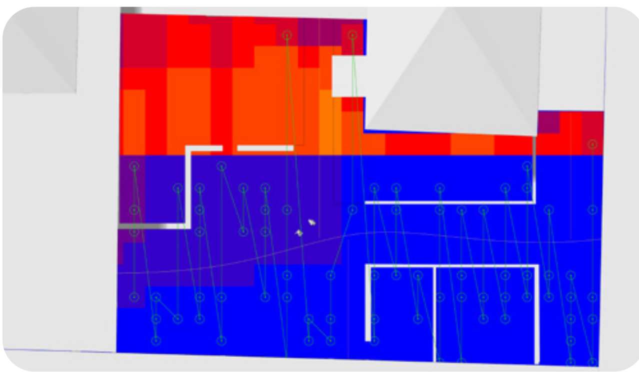


Fig. 8.3.16. 5′ spacing, 120 number, 3 seed - sunlight hour study.

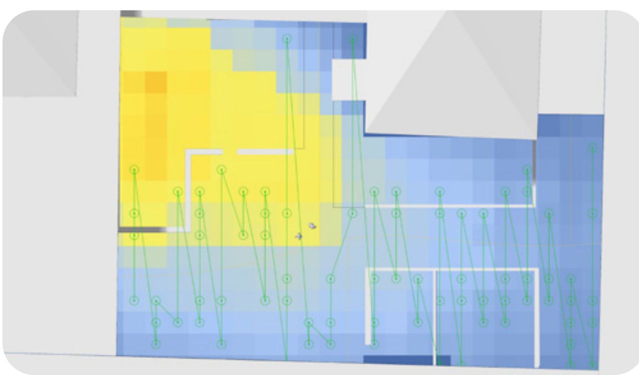


Fig. 8.3.17. 5′ spacing, 120 number, 3 seed - solar radiation study.

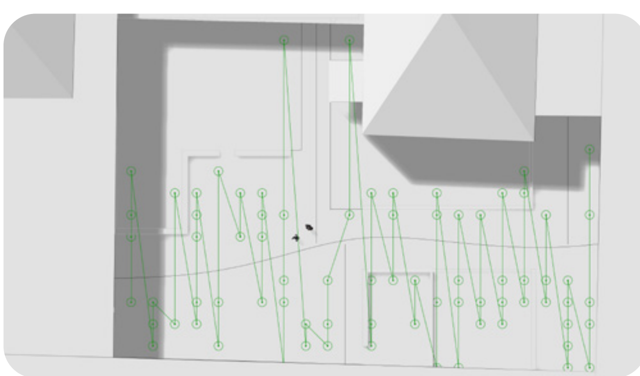


Fig. 8.3.18. 5′ spacing, 120 number, 3 seed, top view.

functional and aesthetic decision. I then explored 1, 2, and 3 seed options by selecting 5′ spacing with 120 as a number. The seed that created the optimal room patterns was the third seed. By exploring different seed and number combinations, I realized that the assembly with the higher number of 120 was most fitting as there were fewer columns and allowed for gallery or room-like spaces within the matrix of bryobead columns.

From Grasshopper, the geometries of the piped columns with bryobeads, vertical pipe, base circles, and irrigation pipe were baked into Rhino and then brought into Twin Motion. Rendering the mosses on bryobead columns gives materiality and functionality to the forms. The irrigation pipe connects from the building to the tops of each column, dripping water in an equal distribution of each vertical perforated pipe. The distributed moisture to the bryobeads aids in helping the mosses to metabolize and turn green. If the infrastructure lacked hydration and the mosses were established, the mosses would go dormant and serve as a softer element on the columns. The matrix would function in all weather conditions and offer aesthetic, cooling, air filtering, and shaded benefits without blocking views. At the base of the columns, a circular moss platform helps absorb runoff, and rocks additionally grow moss and help deflect any hard-pouring water.


Fig. 8.4.1. Bench.

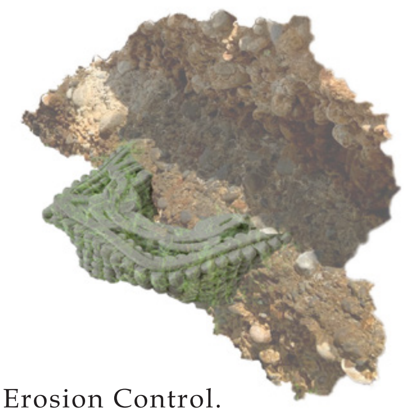


Fig. 8.4.2. Erosion Control.

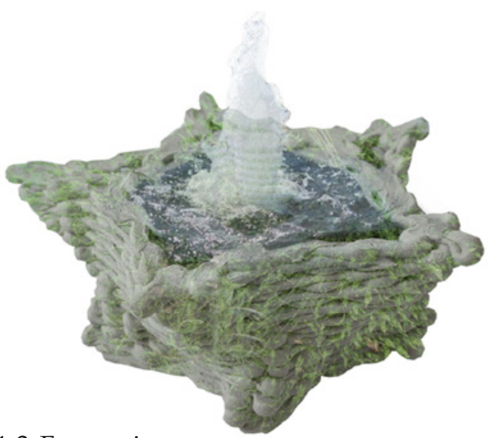


Fig. 8.4.3 Fountain.

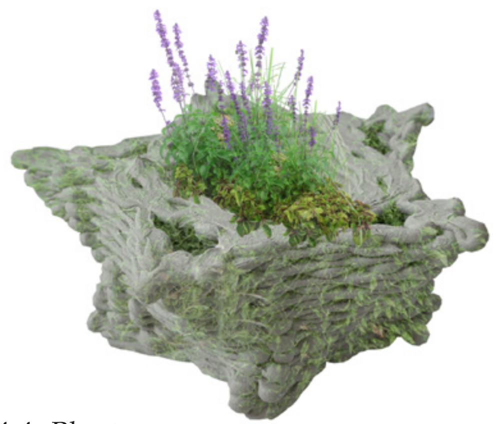


Fig. 8.4.4. Planter.


Fig. 8.4.5. Table.


Fig. 8.4.6. Receptacle.

8.4 LANDSCAPE INFRASTRUCTURE

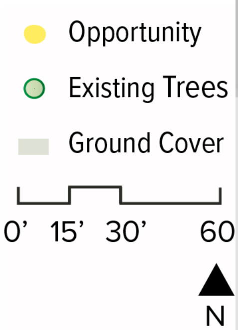
The geometries of the base, capital, and shaft were scaled to explore possible landscape furniture. This projective work was scaled in proportion to its original print, however it was not scaled in relation to the other forms. All the forms could be printed with access to a larger scale printer and could serve the function of propagating mosses.

The base could function as a bench and holds the ability to seat several people with an interior opening. The base could also be inserted to a bank to act as a retaining wall where moss and the hard infrastructure would help hold the soil in place. The capital, scaled a bit larger than the base could function as a fountain and planter. The upright shaft could serve as a table and as a receptacle.

For the final design, the forms were scaled at 13.5X, 15X, and 30X respectively to create the landscape furniture, fountain, and sculpture. A visual survey of the Lawrence Hall courtyard determined the placement of the scaled 3D printed forms. The existing infrastructure of paved areas, garden beds, benches, and lamp were identified and remained intact. Gaps around significant existing trees and shrubs were identified to show the placement of the infrastructure.

Original Size	Base	112mm x 110 mm x 30mm
	Capital	123mm x 118 mm x 56mm
	Shaft	72mm x 72 mm x 104mm
Furniture Scaled by 13.5X	Base	3.5ft x 3.5ft x 1ft
	Capital	4ft x 4ft x 2ft
	Shaft	2.5ft x 2.5ft x 3.5ft
Fountain Scaled by 15X	Base	7.5ft x 7.5ft x 2ft
	Capital	8ft x 8ft x 4ft
	Shaft	5ft x 5ft x 7ft
Sculpture Scaled by 30X	Base	11ft x 11ft x 3ft
	Capital	12ft x 12ft x 5.5ft
	Shaft	7ft x 7ft x 10ft

Fig. 8.4.7. Scaling of forms for courtyard design.



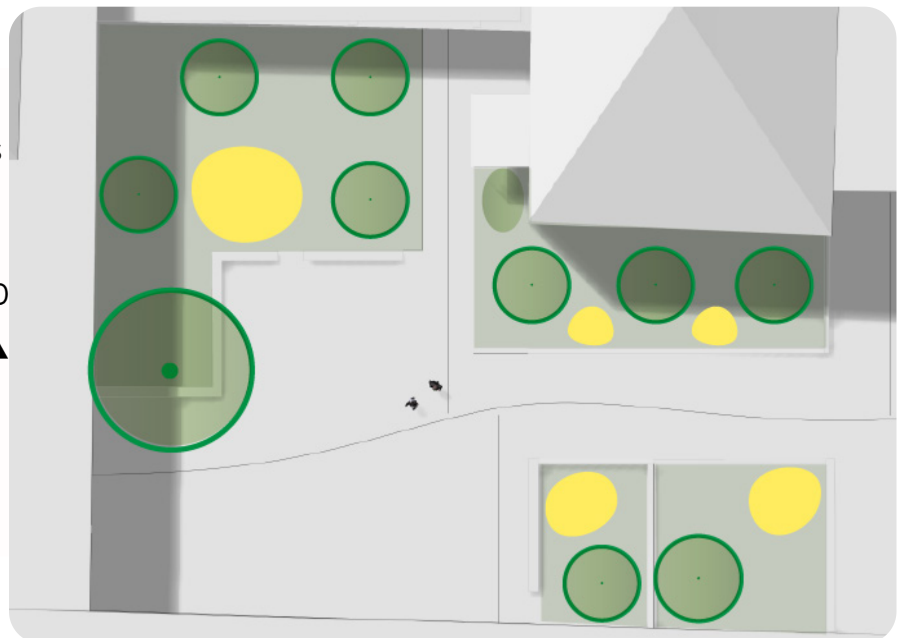


Fig. 8.4.8. Existing trees and opportunities diagram for 3D sculpture placement.

The 1" diameter aluminum irrigation pipe system connects to the water system of the building at the northeast and southwest boundaries of the courtyard. The .78" diameter vertical stainless steel pipes that hold the bryobeads are perforated, allowing water to drain through the pipes and out to the bryobeads to hydrate mosses. The bryobeads are secured by a concrete footing 12" deep into the ground. The dimension of the cylindrical footing is 12" in diameter by 24" in height.

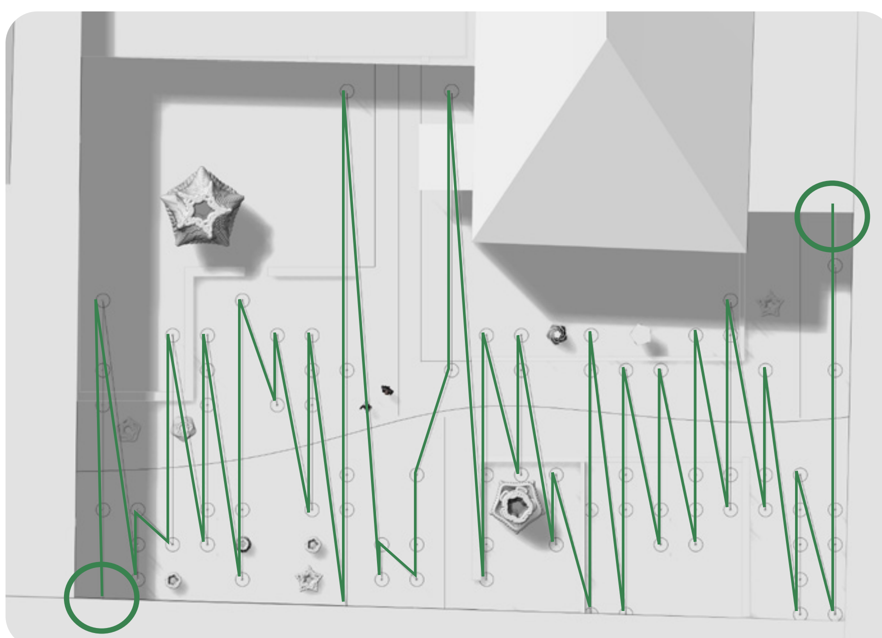
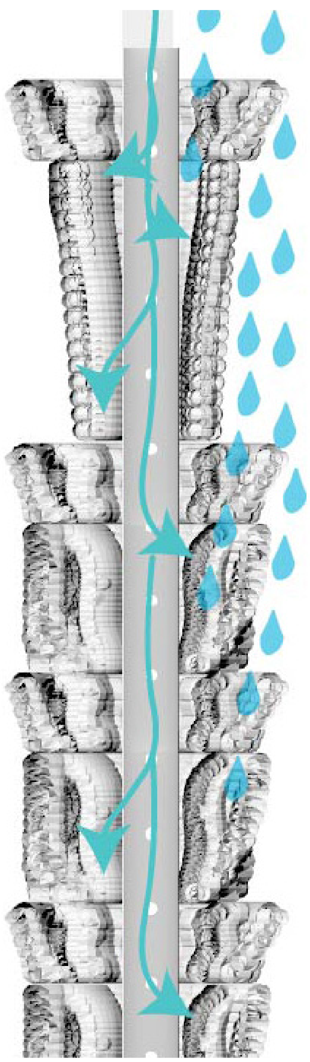


Fig. 8.4.9. Pipe insertion into building at southwest and northeast locations.



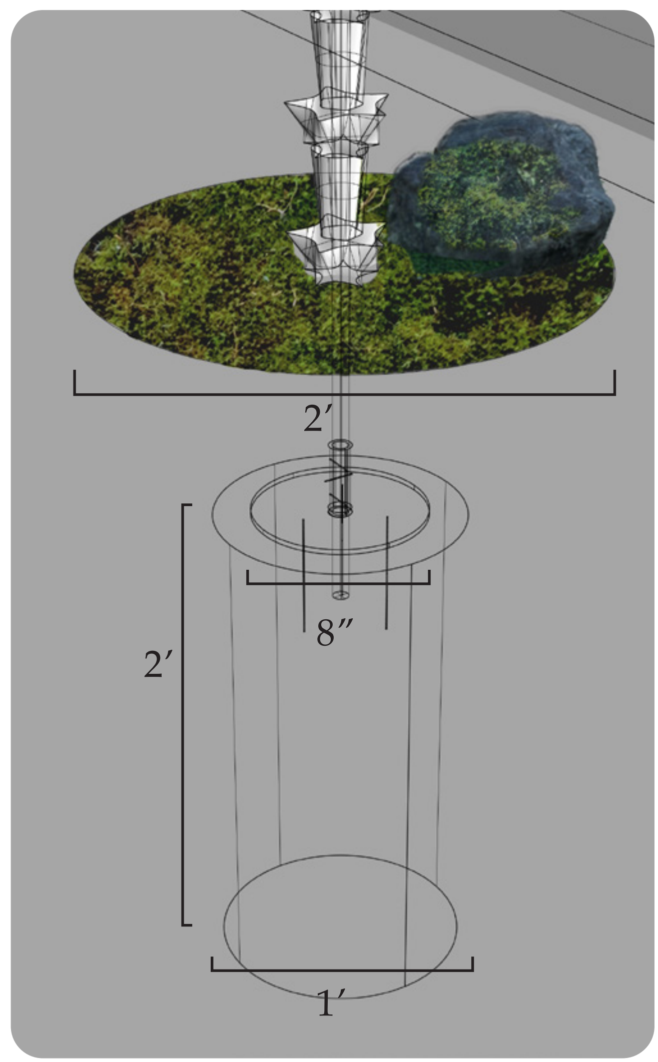


Fig. 8.4.10. Peforated pipe distributing water to bryobeads column.

Fig. 8.4.11. Footing extends below concrete.

Fig. 8.5.0. Plan view, sunny summer day

8.5 BRYOBEAD MATRIX DESIGN

Within Twinmotion, a range of views, seasons, and weather conditions are represented to show the aesthetics and function of the space more clearly. A plan view shows a significant afternoon shadow in the summer protecting the bryobead columns from raking light as seen in Figure 8.5.0. The view looking northeast shows visitors gathering near the printed landscape furniture a table in the foreground and near the fountain and sculpture on a fall sunny day as seen in Figure 8.5.1. The image of two friends sitting on the original concrete bench and the printed base bench show the new and old infrastructure relationships and the potential dual planter functionality form mosses and vascular plants as seen in Figure 8.5.2. In Figure 8.5.3., the view looking west shows the light tree on a summer day and full use of the courtyard space. The cast shadows add a unique visual interest and added pattern to the verticality of the bryobead matrix. Looking west from the main eastern entrance of the courtyard, the capital is shown as a chair used on a sunny spring day, as seen in Figure 8.5.4. This type of bench could substitute for the standard bench that exists in the location.

Looking straight down the path from the eastern entrance on a rainy day, the mosses of the matrix of bryobead columns receive rainfall and bounce back to metabolizing as seen in Figure 8.5.6. Looking towards the eastern door on a cloudy, early fall day, this image shows the fountain as an attraction point, and the motif of the irrigation pipe adding to the visual interest of the courtyard as seen in Figure 8.5.7. In Figure 8.5.8. the sculpture is illuminated, showing the awe and luminescence of a spring evening. The scaled configurations and arrangements of the scaled anemone and bryobeads add value to the ecological, aesthetic, and social potential of the space. The set up of the matrix typology engages closely with a range of users and invites for further learning, speculation, and experiment.

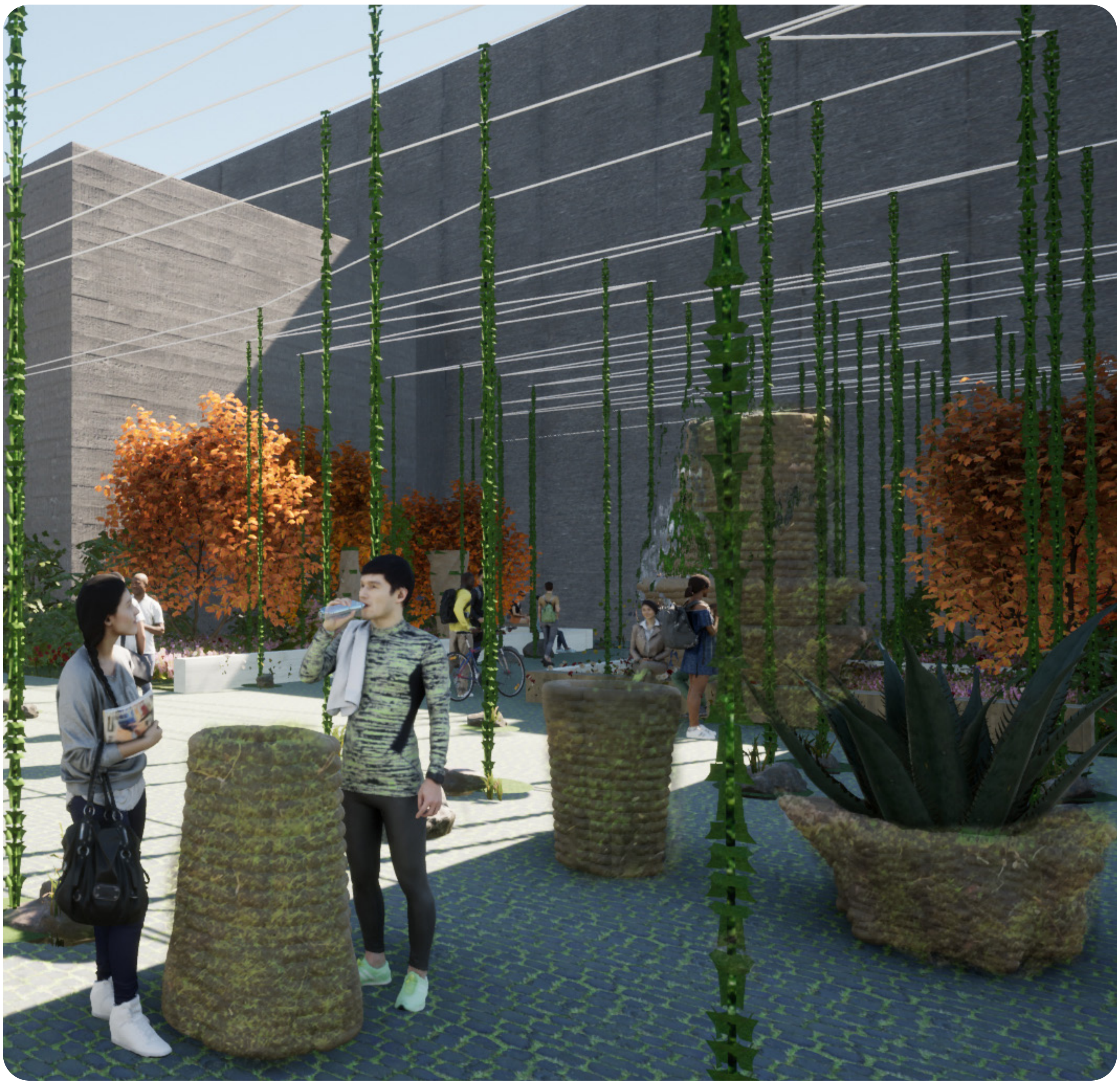


Fig. 8.5.1. Overview, looking northeast: sunny fall day.

Fig. 8.5.2. Seating and Planter, looking northeast: sunny spring day

Fig. 8.5.3. Sculpture and courtyard, looking west: sunny summer day

Fig. 8.5.4. Capital seating, looking west: spring, cloudy day.

Fig. 8.5.6. Lawrence Entrance, looking west: spring, rainy day.

Fig. 8.5.5. Fountain, looking east: cloudy, fall day.

Fig. 8.5.7. Sculpture, illuminated, looking west: evening spring day.

Fig. 9.0.0. Collage demonstrating soil building potential

9. CONCLUSION

This project's scope involved many phases in developing what was learned through research, design, and experiment. Seemingly disparate topics were explored to cultivate greater understanding around their synergies; the benefits of mosses, design of ceramics, the emerging technology of the clay 3D printer. The impetus for this project originated with the locality of living and studying in Eugene, Oregon, and noticing the abundance of mosses, and then learning about the incredible benefits it provides to ecosystems around the world. In the context of landscape architecture, there are exciting ways to shift how we design to work with abundant and resilient plants such as mosses. Furthermore, as designers, we can shape material such as clay and learn about 3D printing methods to design with consistency and complexity on grander scales. This work was explored using research through design by conducting research, rapid prototyping, and further design work to apply what was learned.

While this work is my Master's Project, this work indeed required the expertise of many people working at the forefront of design, bryology, and coding. At the outset of the project, by connecting with Robert Gusek over Zoom, I retrofitted the printer and attained and adjusted the code to run the printer. By learning to use the printer, I cultivated understanding about the relationship of design and the outcome of the print and the many possibilities within emerging technology such as the clay 3D printer. Through the independent study, moving from Rhino to Grasshopper allowed for designing parametrically to develop smooth transitions for determining the toolpath to create successful prints. I approached this work without knowing how to generate a woven toolpath in Grasshopper and using the Cerambot printer.

Within the independent study through design development with Ignacio Lopez Buson and Mary Polites, I learned about the importance of understanding the needs and characteristics of mosses and how their unique qualities could be designed for within the fine and general details of the substrates. Because I was first designing for an experiment, I created similar work with variations without knowing the experiment's outcome. Also, during this time in the fall, I cultivated knowledge on mosses in David Buckley Borden's Research by Design studio. I speculated on how this work could advance into applications in the built environment. Subsequent design work throughout the project during the experiment aimed to respond to the designs to create work that pushes existing landscape infrastructure typologies.

Through the process of design in a software program to the output of the printer, I learned that design outcomes are informed by their tools. Even if the tool does not require manipulation of the hand, such as in the 3D clay printer, tools serve as an extension of our body and ideas. The tools additionally respond to environmental conditions. In many ways, the experiment synthesized these interactions, testing the interaction of the moss on designed substrate and the results of designed substrate hosting mosses responding to environmental conditions and the maintenance of watering. The way we use technology is beneficial, and there is much more to learn to synthesize better ideas for enhancing ecology in the built environment.

During the experiment, I learned that maintenance matters during the propagation stage and that shadier areas with greater grooves are more performative than substrates with greater solar exposure and fewer grooves within the three-month duration of the experiment. The four experiments and substrates revealed similar information that can be taken forward with a more prolonged experiment duration. This work was tracked with climate data and analysis that can be applied to further designs. An important disclaimer for this work is that the visible green growth is called protonema as the first phase of moss growth. An expert has not examined the green material under a microscope, so this demonstrates that this outcome is speculative at this time. With further monitoring and maintenance, and the appearance of a moss structure, this work is a proof of concept that mosses can grow on 3D printed ceramic substrate.

The development of the design work allowed for extended design iterations. I learned throughout the process about the benefits of making work modular and transferable to a range of spaces. These ideas led to the development of a bryobrick screen and finally to a bryobead matrix. I am interested in creating flexible systems that can be transferred to different spaces within the built environment and offer environmental benefits to the greater community. The designs of the rapid prototypes were informed or limited to the capacity of the printer. Patterning the designs through aggregation allowed for impact with current design constraints. I was scaling the work related to prospective design work with what would be possible with access to more excellent technology.

Tangential design exploration investigated drawing with clay and emulating the printer with my hands during the creation of the work. The scanning process to create a mesh and reprint it to see if it could successfully print this work is exciting. There is much to explore during the digital translation process, with the ability to scan existing information and manipulate the data to reshape it with new material; along with this design exploration considered using different scripts for form-finding such as in using anemone. Anemone develops looping patterns that produce forms that would be suitable for translating in the printed form.

With the climate crisis and the need to consider how we design, it is vital to think about how we can best contribute to the environment's health. Creating greater circulation in the economy by using waste materials and generating energy can be addressed with further exploration between clay, moss, and digital technology such as 3D printing. The incorporation of mosses in suitable environments can have hyperfunctional qualities. As landscape architects, we can think about how we design with other fields and across scales using new materials and technology to push the boundaries of what it means to be a landscape architect.

Conducting research on the intersection of mosses and designed clay through this experiment can lead to new design applications in the landscape. The interaction of biota and abiota aims to add ecological performance to the urban landscape beyond aesthetic applications. This research-through-design work produced with the tool of the 3D printer serves as basic research for designers in the field of landscape architecture and at intersecting fields. While what was documented in this project can lead to new insight, there are still many unknowns about what has and is taking place between the substrates and mosses. This work shows that designing with simple materials, in suitable areas, and on a small scale holds potential for making a meaningful impact in the landscape.

Fig. 9.1.0. Aaron Woolverton presenting his work on Algae as Agents.

Fig. 9.1.1. Opening of the exhibition with barnacle experiments in foreground.

Fig. 9.1.2. Sharing about experiment set-up process and results.

9.1 EXHIBITION: FOREGROUNDING

On May 20, 2021, Aaron Woolverton and I, both finalizing our Master's Projects co-hosted a one-evening exhibition to bring our cohort and Master's Project chairs together to share our work in-person. We found an intersection in the focus of our work of understanding the relationship between biota such as mosses and algae and their relationship with abiotic infrastructure and design.

Making our work visible through an artist talk and exhibition was important because while much of our work was processed digitally, our work explored experiment and physical production. The physical presence of the objects helped the viewers to understand the materiality and scale of the work, something that is difficult to comprehend through a digital presentation. There was also a sensory component of touching the work, seeing the work up close, and even listening to the barnacle interfaces convey water.

The artist talk facilitated exciting questions, new ideas and brought a greater sense of understanding to the work.

Fig. 9.1.3. Talking about rainscreen and bryobrick prototyping process.

Fig. 9.2.0. Moss Voltaics Project // IAAC OTF student E. Mitrofanova // IAAC Faculty: S. Brandi, A. Dubor, L. Fraguada, P. Bombelli.Collaboration: Ceramica Cumella. Site Accessed: 5.6.2021. http://www.iaacblog.com/programs/syllabus_urban_biosystems_18/.

9.2 FURTHER RESEARCH

In response to the content of the work that investigated the potential of mosses growing on ceramic surfaces, ideas hinged on this work ask for further research. Extended themes for development mentioned here range from material composition to energy flow and are genuinely limitless.

Biophotovoltaics utilize the energy of plants, and energy produced during photosynthesis by mosses can be harnessed. This can be an inexpensive approach to generating energy where mosses grow. Because mosses require little light, this kind of energy can be produced in less sunlight where conventional solar photovoltaics are less effective.

Mosses' high surface area to mass allows for increased absorbency and moisture retention for more extended periods. Mosses act as a cooling agent and can offset the Urban Heat Island effect. With further research and advanced modeling, the potential impact to reduce the temperature, slow runoff, filter runoff, and reduce noise in the context of certain designs can be measured to work towards sustainable goals.

While observing the interfaces of the experiment, small insects noted to have been traversing the surface, and evidence of engagement was left in spun webs. The dimensions of this work can be scaled up and tailored to serve as a habitat for specific species, especially those impacted by urban development, to enhance ecology.

This work involved working with a recipe from a local clay manufacturer for producing consistent work. The content of the clay body can be modified to include other materials that are used as the byproducts of waste, such as solid waste or the introduction of urine instead of water. Other organic substances can be pulverized to act as a binder to strengthen the material outcomes.

Mosses being one of the first biotas to colonize new land, can help rebuild the soil and prevent erosion, such as during post-wildfire events. Approaches to remediation such as brownfields can function artfully over time. This work can be socially engaging and invite the community to learn about the importance of designing with the landscape ecology.

Fig. 9.2.1 Process of printing barnacle interface #1.

JOURNAL: DESIGN FOR EXPERIMENT

10/6/20

During my first meeting with Stacy Jo Scott, my professor in the independent study for 3D printing, we discussed a range of items to get geared up to print. She mentioned that silkworm is gcode generating, so I could look there to create a script for the Cerambot printer. For materials, we discussed the importance of working with clay that is porous, low-firing, and large grained. For achieving greater porosity, slightly under firing the work will help. Also, adding short, organic materials such as sawdust will help. Stacy Jo recommended testing samples of composition from 5-10% of sawdust. I went to Georgie's to pick up 100 pounds of dry clay mix for mixing clay to achieve the proper consistency. To ensure good mixing, I learned that it would be wise to invest in a refurbished KitchenAid. Other recommendations were printing 1" tall cylinders to test the composition of the clay. Another important insight was to track my work in a Google spreadsheet, to be able to return to failed and successful work to grow competency.

10/13/20

This week I explored tiling objects as I thought it was important to identify a form that would ultimately tile for carrying out moss growth on a larger scale. I explored this process by starting with an equilateral triangle. From the centroid of this shape, I drew a line perpendicular to the midpoint of the edge and to its corner point forming a triangle shape. This small triangular shape was cut from the triangle. I duplicated this shape and rotated it by 120 degrees so that it was aligned to the bordering side of the original triangle. I tessellated the shapes together and realized that there was an overlap at a sharp point. I realized that by trimming the sharp edge from one side of the triangle, that there would be more opportunities to tesselate this shape.

To understand the possible arrangements of the tiled shape, I rotated each one in 6 directions and labeled the orientation. From here, I came up with 3 types of arrangements interlocking 2 shapes. From this, I was able to arrange all 3 combinations together to form a sort of arc. By rotating the arc of the interlocking shapes at 6 different angles, the forms formed a new configuration that could be further tiled. The first configuration resembled a snowflake. From here, I continued to tile the forms with varying gaps to create 4 different types of interlocking configurations. Each arrangement looked slightly different.

In my meeting with professors Mary Polites and Ignacio Lopez Buson, it came to my attention that exploring tiling forms is fine, but does not make sense to explore with the tight line interlocked application. The forms lack dimensionality in the way I explored their connections in Rhino and would not work with the rigid three-dimensionality in clay and natural slumping and variation in surface material. The conversation with them inspired me to consider simple tiles of opposing sides of a form meeting to develop a structure.

10/20/20
My first approach involved starting with drawing silhouettes of possible forms on graph paper. I worked on a grid of 10 units by 10 units. I explored moving the innermost or outermost point one unit and two units away from the original line on the z axis. After drawing 24 possible surfaces, I decided to go with a form that was 1 unit offset from the base of the cylinder to create a design with less of a slope for a more successful outcome. The height of the indent was placed 6 units from the base and 4 units from the top. In Rhino, I translated the convex and concave folded surfaces to opposing sides on a 100mmx100mm cylinder so that they could interlock. I printed this form in a clay combination of clay and 10% sawdust which was successful for the print, however the print only reached 75% because by the time I was able to print the form after running tests and troubleshooting, the cartridge had run low on clay.

I appreciated the crease in the form of the cylinder but found the shape to be a bit too orthogonal and wanted to explore a lofted surface that had an angled crease along the z axis. In rhino, I began by drawing the range of lines by lofting 6 bent lines indenting at one unit along the x axis. I moved out each of the lines equally apart so that they formed a polysurface with a diagonal loft on each side and arranged so that the form would interlock on opposing sides. This was an interesting approach and I enjoyed creating the geometry in Rhino. The major vulnerability in the form here is that there were gaps between each edge of the lofted surfaces which I then patched to close the form. The patches formed unknown geometry between the surfaces, so the predictability is lacking in how the forms would tessellate.

10/24/20

Today I started with a lofting script that I learned from Ignacio Lopez Buson last week where I was able to loft three curves and soften the geometry with a radius and visualize the thickness of the form. Moving the design from Rhino into Grasshopper is an effective step in generating smooth and precise geometry. Working in Grasshopper also allows for making rapid iterations by adjusting a few parameters and after creating forms, allows for feedback for advancing the work.

My first approach to documenting my process was setting up variables in excel such as object, dimension, number of curves, loft type 2/3, height of middle curve, z rotation of middle curve, horizontal rotation of bottom curve, horizontal rotation of middle curve, horizontal rotation of top curve, radius fillet, thickness visualization, and if the forms interlocked.

I worked on a few simple iterations and it seemed tricky to try to align the forms using this route by guessing how the angles of the curves might align. Aaron Woolverton was sitting next to me at the time I was exploring possible iterations and he is proficient in Grasshopper. We were talking about the original form that I designed using the bent lofted surfaces. He came up with a way to take this concept forward by playing with the amplitude in the XY direction and dividing the corner z curves into alternating 1/3 and 2/3 to create surfaces that would closely mirror each other on opposite sides.

The variables I changed to create a new seamless form with this route included playing with the amplitude and xy rotation of the middle curve. I would like to create successful forms where the slope of the sides is interesting, but not too great, so that the relatively flat form can support itself. I used either 15 or 20 for the degree rotation and amplitude, and 10 and 20 for the radius.

My first print was a 100 x 100 mm 15 rotation of the middle curve with 15 amplitude, and 20 radius for the corners. The print looked great until it had printed to about 90% and then it collapsed. After analyzing the geometry of the form, the middle curve looked like a bowtie in section and would actually not tile if the form was not rotated. I further altered the form my making two adjacent z curves at the same height and the other two adjacent curves the same height. This would likely offer greater opportunity for the forms to tessellate.

Options for moving forward include scaling the print down to 80% the size. This was effective last time when I printed the first lofted brick designed in Rhino. Scaling the size down is not preferable because the clay shrinks in size after printing to when it is bone dry, and then again after the bisque firing process.

Unfortunately, after loading the clay for the downscaled print, the printer was making oscillating sounds and the clay was not pressing through with the force of the stepper motor. I took apart this part of the printer and noticed that the plastic gear shaft had come off of the stepper motor and was crunched on the interior.

The way to replace the plastic gear shaft is by 3D printing it in plastic from a simple download on Thingiverse. Hopefully, I will be able to pick up the gear shaft this week and have the printer up and running this weekend.

10/29/20

With Stacy Jo Scott, we talked about structural issues with 3D printing. At 3dp.com, there is information overhangs and how to master them. I have been using the 5mm nozzle and it was recommended to buy a collection of various sizes from cell link. I hesitated on this purchase because I enjoyed working with the fat extrusion considering I will be printing with moss. Also, with removing the extruder, I needed to adjust my Simplify3D set up, and this would be slightly tricky to adjust to accommodate for the nozzle again. I learned that it would be good to check out a variety of guides produced by Jonathan Keep with tutorials exploring 3D printing in clay. I was encouraged to try printing with sawdust at ratios that ranged from 2.5% 5, and 10%. Stacy Jo mentioned I could also test the ratio of the clay body by rolling it into a coil and bending it and this is where I shared that the clay consistency I am working with is much more viscous like toothpaste in comparison to what works with other clay 3D printers. I had some issues with clay adhering to the wood, so I was also advised to cover with wood with plastic wrap. I also learned that if I was able to print a larger skirt and decrease the 1st layer height of the print, that this solid start with help with the success of my prints.

11/1/20

This last week I was able to find a replacement for the gear shaft on Thingiverse through Cerambot support. Luckily there are 3D plastic printers printing in PLA at the Craft Center at the University of Oregon. I was able to have three parts printed within the week. I drilled the impressed and cracked plastic gear shaft out of the insertion of the gear. I was able to bang out the broken parts. The gear shaft fit perfectly around the protrusion of the stepper motor. I thought I would need glue to adhere it, but it wasn't necessary because of the facet on one side serving as a key. The printer has been reassembled and is back up and working!

11/4/20

While meeting with Mary and Ignacio last week, we discussed the reason why the form is collapsing and considered design variables that could be implemented to prevent the brick from collapsing. One option is to consider softening the geometry from top view so that the nozzle will not make abrupt moves and angles which weakens the structure during the print phase. This means that considering a cylindrical form where the tangents of the angle are greater will be less will be more optimal in that it will be less stressful for the clay. For example, a 15-degree tangential angle will be less promising than a 30 degree tangential angle curve. Another option is to consider intersecting radial geometries such as a clover formed by 4 open cylinders to reinforce the balance of the structure.

After having my midterm in studio last week and presenting on my idea for generating 3D printed surfaces in clay and ceramic, I was asked which parameters I am focusing on for my research. There are parameters that I am working with between the properties of clay, the output of the printer, and the preferences of moss growth.

11/6/20

During our weekly meeting on November 5th, I presented a few new iterations of bricks that were an extension of designing from three lofted curves in grasshopper to create a lofted brick. Something that I was interested in improving on for this new design iteration was working with smoother lines and a conical shape that would be able to increase water catchment. The bricks for the first couple iterations were exactly the same and tiled nicely in concept. I have realized that through this design process, I have been needing to be more clear about which question I am answering: am I designing an experiment for a system to understand moss growth or is this an experiment about developing brick to host moss? I am working to design a system to understand moss growth which I think can open up more design possibilities and re-thinking how I am approaching designing the brick.

Something in question during the meeting related to the importance of having the shapes tile cleanly. I was using the word tessellate, but a more appropriate word to describe this is clustering or aggregation as tessellating relates to physics or chemistry. I presented an idea that I had explored in an Overlook theory class last spring with interest in exploring the barnacle form.

Exploring the barnacle form is attractive because the form is conical with interior and exterior surfaces for the moss to grow on and be visible. In the former brick patterns, the bricks would pack in a way where only the interior surface would be visible except for the perimeter of the cluster. The arrangement of a range of slopes and sizes for the barnacles would fit closely along the base. This infers that the experiment relates more to landscape and does not need to have structural integrity.

In nature, barnacles are composed of a layered system with bumps at the corners. Barnacles exist in some of the harshest conditions of the earth and are very resilient in their structure. Their interior and exterior forms create microclimates. The geometry of the forms is also softer and not as angular as what I had formed in the grasshopper script. Ways to improve my existing script include filleting the corners at the top and twisting the top. Ideally where lines of stress are along the corners, it would be suitable to create a bumpier pattern for reinforce the corners. Moving forward, I will be testing a ratio of scales of slope, height, aperture opening, fine grain and large grain of the pattern.

11/6/20

Selected one form from the grid and printed it twice. Printed at two different speeds. I experienced a breakthrough in being able to generate a polyline from one of the meshes to export the form directly from grasshopper to the printer. This is great because now I can apply and investigate the grain of the form.

The slower speed seemed too slow at first with the building up of clay, so I decided to speed up the print. The second print seemed to have less structural integrity in that there were more gaps and extreme sagging.

The largest barnacle printed well to the end. In my grasshopper definition, however, there is an offset line on the perimeter that creates a sort of ledge that ultimately affects how water runs down the exterior of the cone. While setting the print on the table, the print actually collapsed. The clay was wet in consistency but seemed to have structural integrity. Something that I would to do to strengthen the surface is to further rotate the shapes at the top. I also increased the fillet to soften the edges. Another characteristic that I am interested in is making the barnacles more conical by billowing out the shape. The winding weaving surface to the top of the form could have a more interesting surface application.

11/14/20

Today, I rotated the top curve of the barnacle and am looking to add attractor points to the surface to create slight concentric circles displaced from the surfaces. This creates a macro groove which would compliment the form. I am interested in articulating the main form, the macro surface texture which this would be and the weave. The weave that I worked with last week was at 9 amplification and could be amplified further to create a more interesting surface. (11/19) I am no longer interested in working with a meso-texture as this process has been precarious enough with the printing and have been dealing with too many collapsed prints. The only other idea that I would be interested in investigating is randomizing the amplification within a range to achieve varied grooved texture for creating greater variability within the surface.)

11/19/20

This week, with the help of Ignacio and Mary, I was able to work with a much improved and shorter script that allowed the top layer of the curve to match with the others, so when printing to its entirety, the form will not be thrown off balance with a dangling coil because of the outlying curve. I also received the hint from them for rebuilding the surface using loft options. This makes for a smoother surface and allows the definition to work using curves and not a polyline. As far as I can tell at the moment, this creates a more balanced form that will not be affected by the change in amplification from one corner to the next and also from side to side that has created significant issues in the past.

11/22/20

When meeting with Ignacio and Mary for our last meeting, I concerned because most prints I was generating from the barnacles had been collapsing. We talked about incorporating a gradation of amplification ranging increasing greater wall thickness at the base towards a thinner wall at the top of the forms. In the previous prints, the amplification of the walls varied from one corner to the other creating instability across the form leading to collapse. Based on the number of points used, the width of each layer was slightly different, shifting the amplification. To control the amplification of points along the z axis, we deconstructed the points, remapped the values creating a range of bounds. To help visualize this work, I learned about the plug-in Fologram to visualize the thickness of the extrusion as a piped mesh prior to printing. This visualization helps to point out weaknesses and detail layer overlap construction. Furthermore, when using the clipping plane, it is possible to see the work in section. I found that this exercise was like what potters do to check their work – by slicing through pots to examine the construction. With this improved script and new visualization method, I was able to print a 10-group cluster of barnacles. The only additional issue I have been running into is that on almost half of the works, the curve dips into the second layer of the top which causes the nozzle to flatten and distort the work. I have been manually trimming the curve and generating gcode from the new curve to update the forms.

11/30/20

Stacy Jo and I recapped the work for the term and returned to previously discussed topics. I finally began to cover the wooden base plates with plastic for better clay adhesion to the print bed and balanced drying to help maintain the integrity of the form. We confirmed firing the work to cone 06 to help foster greater porosity in the work. After talking about the focus on porosity, I decided to add the composition of sawdust to the experiment. I had let go of testing with sawdust during the time I was trying to print successfully with regular clay. I learned about a new connection in clay for firing work on campus independently of the ceramics firing schedule.

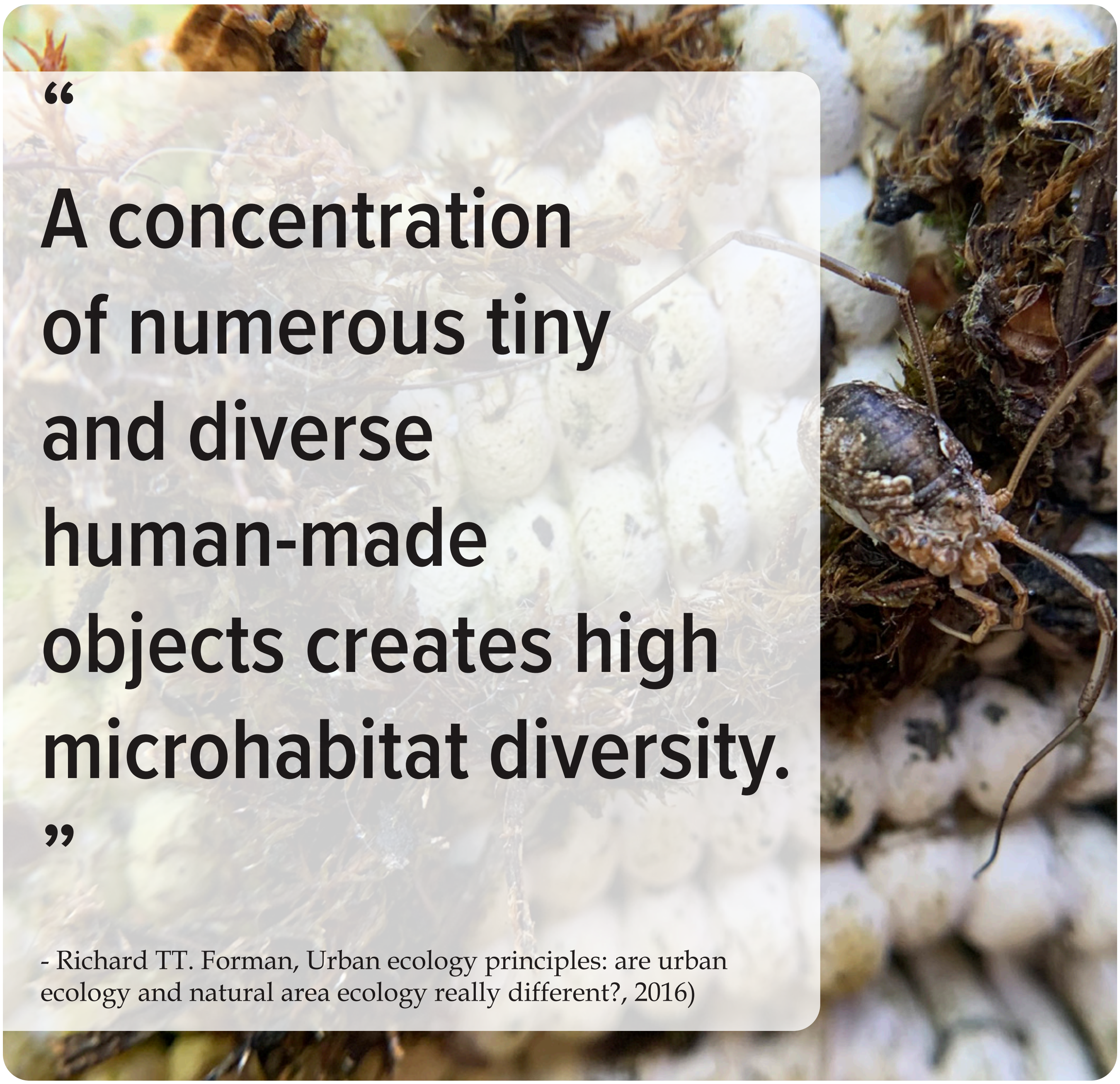


Fig. 9.2.2. Macro photography image of Home experiment with spider.

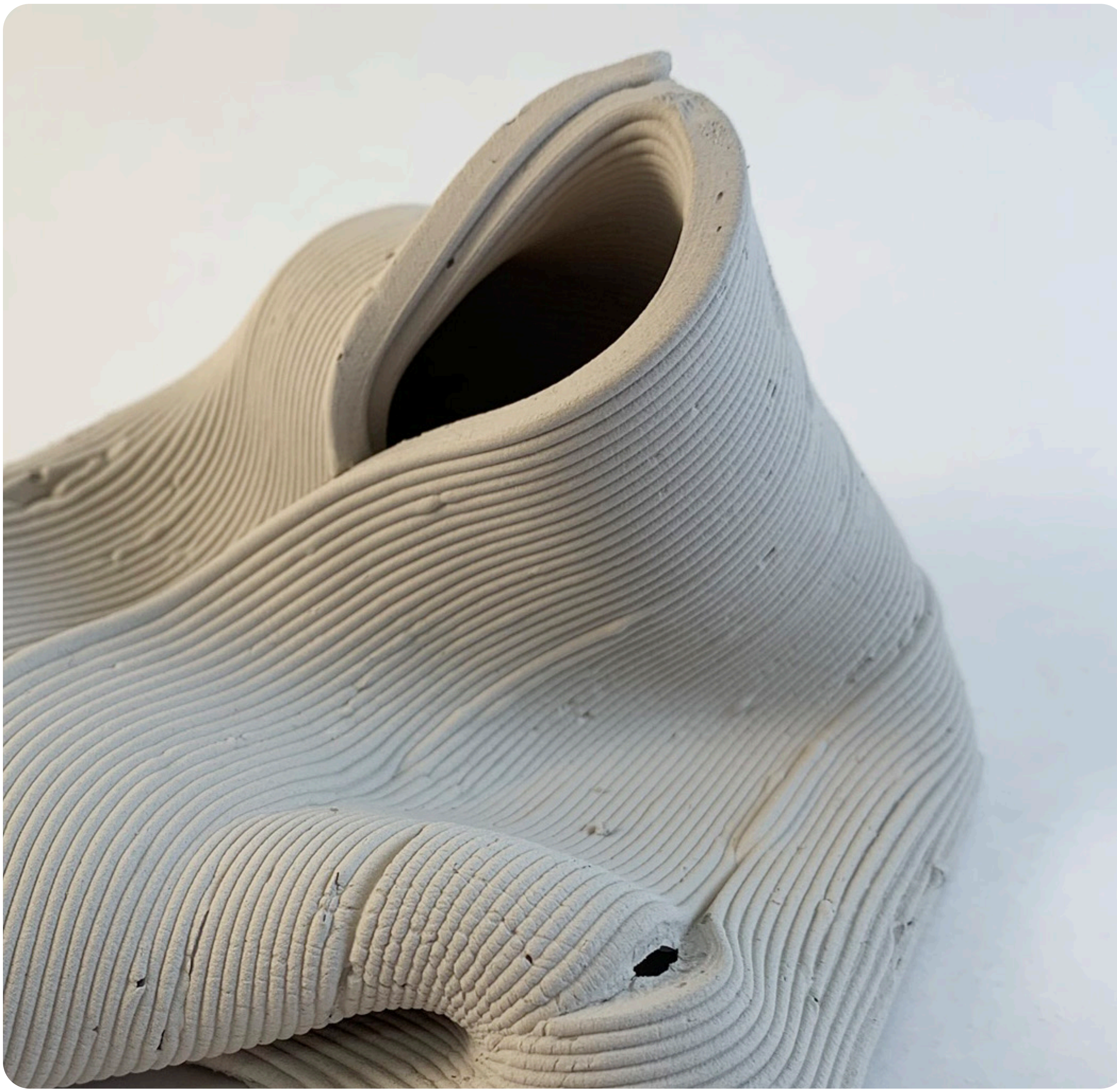


Fig. 9.2.3. Early lofted brick design; collapsed at 90%.

REFERENCES

Architectural Terra Cotta Manufacturer Boston Valley Terra Cotta. *Boston Valley Terra Cotta*, https://bostonvalley.com/home/. Accessed 26 Aug. 2020.

Ceramic 3D Printing: Art and Mathematics. *Slip Rabbit*, https://www.sliprabbit.org/book. Accessed 30 Aug. 2020.

Econcrete. *ECOncrete*, https://econcretetech.com/. Accessed 27 Aug. 2020.

Jeff Schmuki, Artist, Sustainability, Ceramics, PlantBot Genetics. *Jeff-Schmuki*, https://www.jeffschmuki.com. Accessed 26 Aug. 2020.

Learn How to Get Started With 3D Printing in Ceramics |. *Pinshape 3D Printing Blog | Tutorials, Contests & Downloads*, 21 Apr. 2017, https://pinshape.com/blog/3d-printing-in-ceramics/.

People. Slip Rabbit, https://www.sliprabbit.org/people. Accessed 30 Aug. 2020.

Terraplanter. *Terraplanter*, https://www.terraplanter.com/. Accessed 26 Aug. 2020.

The 3D Additivist Cookbook. *#Additivism*, https://additivism.org/cookbook. Accessed 30 Aug. 2020.

The Biomimicry Institute — Nature-Inspired Innovation. *Biomimicry Institute*, https://biomimicry.org/. Accessed 27 Aug. 2020.

The Free Beginner's Guide. *3D Printing Industry*, https://3dprintingindustry.com/3d-printing-basics-free-beginners-guide/. Accessed 6 Sept. 2020.

A Tipping Point: Contemporary Ceramics (NCECA) | Northern Clay Center. https://www.northernclaycenter.org/exhibition/tipping-point-contemporary-ceramics-nceca. Accessed 30 Aug. 2020.

Allen, S., McQuade, Marc, & Princeton University. School of Architecture. (2011). Landform building : Architecture's new terrain. Baden, Switzerland : [Princeton, N.J.]: Lars Müller ; Princeton University School of Architecture.

Almusaed, A., Almusaed, A., Abushaik, Z. K. and Khalil, S. (2006). Biophilic architecture, the concept of healthy sustainable architecture. PLEA2006 – The 23rd Conference on Passive and Low Energy Architecture, Geneva, Switzerland. Environment. New York: Terrapin Bright Green.

Bechtold, Martin. (2015). Ceramic Material Systems. Birkhauser.

Benyus, J. (1997). Biomimicry : Innovation inspired by nature (1st ed.). New York: Morrow.

Berndtsson, C. (2010). Green roof performance towards management of runoff water quantity and quality Ecol

Eng, 36, pp. 351-360.

Besir, Ahmet B, & Cuce, Erdem. (2018). Green roofs and facades: A comprehensive review. Renewable & Sustainable Energy Reviews, 82, 915-939.

Browning, W. D. Ryan, C., Clancy, J. 14 Patterns of Biophilic Design, Improving Health and Well-Being in the Built. 2014

Buck, William R, Allen, Bruce, & Pursell, Ronald A. (2006). Recent literature on bryophytes—109(4). The Bryologist, 109(4), 600-610.

Capozzi, Fiore & Carotenuto, Rosa & Giordano, Simonetta & Spagnuolo, Valeria. (2018). Evidence on the effectiveness of mosses for biomonitoring of microplastics in fresh water environment. Chemosphere. 205.

Carr, K.E. (2017). History of Pottery – Clay Pottery. Quatr.us Study Guides.

Chairunnisa, Intan, & Susanto, Dalhar. (2018). Living Material as a Building Façade: The Effect of Moss Growth toward Mechanical Performance on Pre-vegetated Concrete Panels. International Journal of Technology, 9(6), 1266-1275.

Cheng, C., Li, Y. J., Long, M. Z., & Li, X. N. (2019). [Application potential of bryophyte soil crust on the control of karst rocky desertification]. Ying yong sheng tai xue bao = The journal of applied ecology, 30(7), 2501–2510. https://doi.org/10.13287/j.1001-9332.201907.008

Chiari, Giacomo & Cossio, Roberto. (2002). Ethyl silicate treatment's control by image treatment procedure.

Clark, C. H. Niu, J. Zhou, P. Adriaens. (2010). Scaling of economic benefits from green roof implementation in Washington, DC. Environ Sci Technol, 44 pp. 02-08.

Clark, Garth. (2016). "Present Future of Ceramics" (lecture presented by Northern Clay Center at the American Craft Council Library, Minneapolis, MN)

Coxson, Darwyn S. (1991). Nutrient release from epiphytic bryophytes in tropical montane rain forest (Guadeloupe). Canadian Journal of Botany, 69(10), 2122-2129.

Cruz, M., & Beckett, R. (2016). Bioreceptive design: A novel approach to biodigital materiality. Architectural Research Quarterly, 20(1), 51-64. doi:10.1017/S1359135516000130

Cuevas, D. G., & Pugliese, G. (2020). Advanced 3D Printing with Grasshopper, Clay and FDM. Independently

published. https://books.google.com/books?id=2nGzzQEACAAJ
Deming, M. Elen, & Swaffield, Simon. (2011). Landscape architecture research (1st ed.). Hoboken, N.J: Wiley.
Department of Planning and Local Government. (2010). Rain Gardens, Green Roof sand Infiltration Systems. Government of South Australia, Adelaide; 12–21.
Dethier, J., Eaton, Ruth, & Centre Georges Pompidou, host institution. (1982). Down to earth : Mud architecture, an old idea, a new future : Based on an exhibition at the Centre Georges Pompidou. London: Thames and Hudson.
Eliasson, I. (2000). The use of climate knowledge in urban planning. Landscape and Urban Planning, 48(1–2), 31–44. http://dx.doi.org/10.1016/S0169-2046(00)00034-7
Fromm, E.O. (1964). The Heart of Man. UK: Harpercollins.
Archdaily, (2017). "This Copenhagen Diabetes Center Connects Patients to Nature". https://www.archdaily.com/803283/this-copenhagen-diabetes-center-connects-patients-to-nature. Accessed 12/8/2020.
Flora of North America Editorial Committee, eds. 1993+. Flora of North America North of Mexico [Online]. 21+ vols. New York and Oxford. http://beta.floranorthamerica.org. Accessed 3.6.21.
Garty, J., 1992. The Postfire Recovery of Rock-inhabiting Algae, Microfungi and Lichens. *Canadian Journal of Botany*, Volume 70, pp. 301–312
Getter, K.L D.B. Rowe, G.P. Robertson, B.M. Cregg, J.A. Andresen (2009). Carbon sequestration potential of extensive green roofs Environ Sci Technol, 43, pp. 7564-7570.
Glime, (2007). Bryophyte Ecology. Chapter 2 http://flora.huh.harvard.edu/FloraData/001/WebFiles/fna27/FNA27-Chapter2.pdf
Goffinet, B., & Shaw, A. J. (2009). Bryophyte biology. Cambridge: Cambridge University Press.
González, A.G., Pokrovsky, O.S. (2014). Metal adsorption on mosses: Toward a universal adsorption model, Journal of Colloid and Interface Science, Volume 415, Pages 169-178,
Groat, L., & Wang, D. (2002). Architectural research methods. New York: Wiley & Sons.

Hargens, Ursula. Lecture series on ceramic history in the MN Nice Program at The Northern Clay Center. 2016.

Hasselquist NJ, Metcalfe DB, Marshall JD et al (2016) Seasonality and nitrogen supply modify carbon partitioning in understory vegetation of a boreal coniferous forest. Ecology 97:671–683

Heringer, Anna, et al. *Upscaling Earth: Material, Process, Catalyst*. gta publishers, 2020.

Jonathan Keep, Digital 3D Ceramic Printing Journal. http://www.keep-art.co.uk/journal_1.html. Accessed 26 Aug. 2020.

He, Jiang. (2011). A design supporting simulation system for predicting and evaluating the cool microclimate creating effect of passive evaporative cooling walls. Building and Environment, 46(3), 584-596.

Hylander, K. (2005), Aspect modifies the magnitude of edge effects on bryophyte growth in boreal forests. Journal of Applied Ecology, 42: 518-525. https://doi.org/10.1111/j.1365-2664.2005.01033.x

Julinova, P.; Beckovsky, D. (2019). Perspectives of moss species in urban ecosystems and vertical living-architecture: A review. In Advances in Engineering Materials, Structures and Systems: Innovations, Mechanics and Applications. Cape Town, South Africa: CRC Press-Balkema.

Karlsson, Albin, Jonsson, Johanna. (2019).*The Weave. An Investigation into the Intersection of Craft and 3D Printing. Lund University*. Master Thesis. May.

Kayıhan, Kutlu & Ozcelik Guney, Sedef & Unal, Faruk. (2018). Biophilia as the Main Design Question in the Architectural Design Studio Teaching. MEGARON / Yıldız Technical University, Faculty of Architecture E-Journal. 13. 10.5505/megaron.2017.59265.

Kellert, S. (2018). Nature by design : The practice of biophilic design. New Haven, CT: Yale University Press.

Khalili, Nader. (1983). Racing Alone: A Visionary Architect's Quest for Houses Made with Earth and Fire. New York: Harper and Row

Kimmerer, R. W. (2003). Gathering moss : a natural and cultural history of mosses (First). Oregon State University Press.

Ladrón de Guevara, M., Gozalo, B., Raggio, J., Lafuente, A., Prieto, M. and Maestre, F.T. (2018), Warming reduces the cover, richness and evenness of lichen-dominated biocrusts but promotes moss growth: insights from an 8 yr experiment. New Phytol, 220: 811-823. https://doi.org/10.1111/nph.15000

Lawton, Elva. Moss Flora of the Pacific Northwest. Hattori Botanical Laboratory, 1971.

Lenzholzer, Sanda, Duchhart, Ingrid, & Koh, Jusuck. (2013). 'Research through designing' in landscape architecture. Landscape and Urban Planning, 113, 120-127.

Little, B., (2001). Building with Earth in Scotland: Innovative Design and Sustainability. Scottish Executive Central Research Unit, Scotland.

Lindo, Zoë, Nilsson, Marie-Charlotte, & Gundale, Michael J. (2013). Bryophyte-cyanobacteria associations as regulators of the northern latitude carbon balance in response to global change. Global Change Biology, 19(7), 2022-2035.

Mansour, H. (2012). Biomimicry: A 21st Century Design Strategy Integrating With Nature In A Sustainable Way Proceedings of the First International Conference on Sustainability and the Future, The British University in Egypt.

Marscommons. marscommons.marsdd.com/3dprinting/tech-trends-new-applications/

McCune, B. and M. Hutten. 2018. Common Mosses of Western Oregon and Washington. Wild Blueberry Media, Corvallis, Oregon. iv+148 pages. ISBN 978-0-9987108-2-2 (pbk.)

McCune, B. (2014). Oregon State University. https://mosslandscapes.weebly.com/

Minke, G. (2000). Earth construction handbook : The building material earth in modern architecture (International series on advances in architecture). Southhampton [UK] ; Boston: WIT Press.

Nijhuis, Steffen, & Bobbink, Inge. (2012). Design-related research in landscape architecture. Journal of Design Research (Geneva, Switzerland), 10(4), 239-257.

Niroumand, Hamed & Zain, M.F.M. & Jamil, Md & Niroumand, Shahla. (2013). Earth Architecture from Ancient until Today. Procedia - Social and Behavioral Sciences. 89. 222-225. 10.1016/j.sbspro.2013.08.838.

Ochoa-Hueso, Raúl, & Manrique, Esteban. (2011). Effects of nitrogen deposition and soil fertility on cover and physiology of Cladonia foliacea (Huds.) Willd., a lichen of biological soil crusts from Mediterranean Spain. Environmental Pollution (1987), 159(2), 449-457.

Peck, JeriLynn E. (2006). Regrowth of understory epiphytic bryophytes 10 years after simulated commercial moss harvest. Canadian Journal of Forest Research, 36(7), 1749-1757.

Rennie R., (1810). Essays on the natural History and Origin of peat moss, III-IX. Archibald and Constable, Edinburgh, Scotland.

Pohl, G., & Nachtigall, W. (2015). Biomimetics for Architecture & Design: Nature - Analogies - Technology.

Ramzy, Nely. (2015). Sustainable Spaces with Psychological Values: Historical Architecture as Reference Book for Biomimetic Models with Biophilic Qualities. ArchNet-IJAR, 9(2), 248.

Rael, R. (2009). Earth architecture (1st ed.). New York, N.Y.: Princeton Architectural Press.

Rosentreter, Roger. (2020). Biocrust lichen and moss species most suitable for restoration projects. Restoration Ecology, 28(S2), S67-S74.

Sameh, Sherin H. (2014). Promoting earth architecture as a sustainable construction technique in Egypt. Journal of Cleaner Production, 65, 362-373.

Savini, A., & Savini, G. (2015). A short history of 3D printing, a technological revolution just started. 2015 ICOHTEC/IEEE International History of High-Technologies and their Socio-Cultural Contexts Conference (HISTELCON), 1-8.

Shafique, Muhammad and Xiaowei, Luo, Life Cycle Assessment of Green Roofs: A Review on the Current Research (June 25, 2019). Abstract Proceedings of 2019 International Conference on Resource Sustainability - Cities (icRS Cities)

Shaw, A., & Goffinet, Bernard. (2000). Bryophyte biology. New York, N.Y.: Cambridge University Press.

Sier, Kirsty (2017). An ode to bio-receptive concrete. Architecture and Design. https://www.architectureanddesign.com.au/features/product-in-focus/an-ode-to-bio-receptive-concrete#

Spitale, D. (2017). Forest and substrate type drive bryophyte distribution in the Alps. Journal of Bryology 39: 128-140

Searle, Alfred. (2013). The Natural History of Clay. Cambridge University Press.

Steenbergen, C. (2008). Composing landscapes : Analysis, typology and experiments for design (English ed.). Basel ; Boston: Birkhäuser.

Tedeschi, A., Wirz, Fulvio, & Andreani, Stefano. (2014). AAD, Algorithms-aided design : Parametric strategies using Grasshopper (First ed.). Brienza, Italy: Le Penseur Publisher.

Tschumi, Christian A. Between Tradition and Modernity: The "Karesansui" Gardens of Mirei Shigemori Landscape Journal , 2006, Vol. 25, No. 1 (2006), pp. 108-125 Published by: University of Wisconsin Press

Turetsky, MR. (2003). The Role of Bryophytes in Carbon and Nitrogen Cycling. The Bryologist, 106(3), 395-409.

Van Wijk, A. J. M, and Van Wijk, I. (2015). 3D Printing with Biomaterials. IOS Press, Incorporated.

Ward, Alie. (2020). https://www.alieward.com/ologies/bryology, "Bryology (MOSS) with Dr. Robin Wall

Kimmerer."
Walliss, J., & Rahmann, Heike. (2016). Landscape architecture and digital technologies : Re-conceptualising design and making. Abingdon, Oxon [UK] ; New York: Routledge.
Windadri, F. I. (2009). Keragaman Lumut Di Resort Ka-rang Ranjang, Taman Nasional Ujung Kulon, Banten. Jurnal Teknologi Lingkungan, 10(1), 19–25.
Wright, Dorothy. (1992). The Complete Book of Baskets and Basketry New York: Sterling Pub. Co.
Yasui, Kentaro, Tanaka, Ayako, Ito, Kenichi, Fujisaki, Minoru, & Kinoshita, Hiroyuki. (2018). Experimental and Numerical Analyses of Temperature-Reducing-Effect by Heat of Water Evaporation on a Moss-Greening Ceramic Utilizing Waste Silica. Materials, 11(9), 1548.

Fig. 9.2.3. Home experiment, macro photography documentation on 6.3.21.