Recasting Resilience: Bio-based Alternatives for Concrete & Ceramics

By

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UC Davis Land Acknowledgement Statement:

UC Davis pays homage to the indigenous people and land on which the Davis campus is located. Following consultation with members of the Patwin native community, the campus is pleased to provide the following "Land Acknowledgement Statement" that can be used in oral or written form at events as deemed appropriate. The campus encourages those who are interested to use the following language, without edit:

We should take a moment to acknowledge the land on which we are gathered. For thousands of years, this land has been the home of Patwin people. Today, there are three federally recognized Patwin tribes: Cachil DeHe Band of Wintun Indians of the Colusa Indian Community, Kletsel Dehe Wintun Nation, and Yocha Dehe Wintun Nation.

The Patwin people have remained committed to the stewardship of this land over many centuries. It has been cherished and protected, as elders have instructed the young through generations. We are honored and grateful to be here today on their traditional lands.

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I'd like to acknowledge and thank my committees for their tremendous support and accessibility, especially during restricted and uncertain times.

I'd also like to acknowledge and thank Graduate Program Coordinator Melany Miners, Graduate Program Chairs: Glenda Drew and Jiayi Young, Department Chairs: Christina Cogdell and Simon Sadler, Ann & Michael Savageau, and my cohort for all their generosity, resilience and dedication to cultivating this academic program year after year.

Abstract

Increasingly, designers are re-assessing their roles in the relationships between buildings, built environments, and the non-built ecosystems that provide the raw materials and energy that sustain them. Individually adopting greener studio practices and making material transitions are common responses to the climate crisis, biodiversity loss, pollution and the many other interwoven social and environmental injustices of our era. Yet, designers are also innately poised to cultivate unorthodox research relationships that weave disciplines, data, experiences and cultures in projects which then weave broader audiences and deeper mutual understanding. Focusing on the decarbonization of concrete and ceramics, this thesis project initiates a long-term integrated biomaterial research + sculptural practice that cultivates common interests and mutual research relationships amongst Engineering, Microbiology, Native American Studies, Industrial Ecology, Reconciliation Ecology, Architecture, Art and Design. In doing so, it aims to meet the ever-increasing need for the diverse, complex collaborations required to confront the complexities of the climate crisis as well as the ever-increasing need for more effective science communication. The thesis project culminates with the debut of 'Aperiodic Table', a bi-modular, reconfigurable sculpture at the 2021 Manetti Shrem Virtual MFA show. Each module is made from a different biogenic cement composite (BCC) formula. Its geometry is based on Penrose tiling, resembling the aperiodic crystallization patterns which occur in cements at the microscopic level. Like the periodic table of elements or community quilt projects, it is a multi-phase, collaborative project which artists/scientists will add new BCCs to and reconfigure over time.

Introduction

The year 2020 marked many crucial points in human history, including “Global human-made mass exceed[ing] all living biomass” for the first time. (Elhacham, Et al, 2020) After approximately doubling every 20 years over the past 200 years, our anthropogenic mass surpassed Earth’s biomass at 1,108 Gigatons and is projected to continue increasing at a similar rate. While plastics account for 8 Gigatons which is twice the mass of all animals on Earth, it is concrete that makes up the rapid growth of this incredible mass.


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Article | Published: 09 December 2020

Global human-made mass exceeds all living biomass

Emily Elhacham, Liad Ben-Uri, Jonathan Grozovski, Yinon M. Bar-On & Ron Milo

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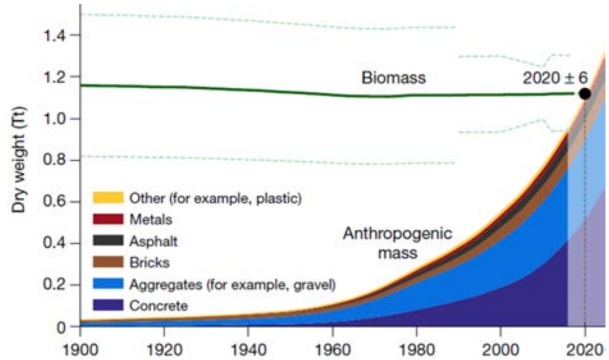


The built environment depends on sand from the unbuilt environment to make concrete and it is now being extracted at a rate of 50 billion tonnes (50 gigatons) per year, making sand the second most consumed natural resource on Earth after water. (Beiser, 2020) Pascal Peduzzi, Director of the Global Change & Vulnerability Unit at the United Nations Environment Programme suggests that “We cannot extract 50 billion tonnes per year of any material without leading to massive impacts on the planet and thus on people’s lives.” As these impacts become more severe and coupled with the climate crisis, every facet of the concrete production life cycle is being reassessed by researchers across fields and across the globe in hopes of reducing the approximately 10% of all anthropogenic CO_2 emissions that come from the production of concrete.

This 2020 anthropogenic milestone was also passed during a global pandemic which prompted additional shifts in our thinking about the built environment, climate, materiality, and systems of production. For many, the combination of pandemic responses and extreme weather responses demonstrated the enormous impacts that microbes and CO_2 molecules have on our lives and our planet. For designers, it provided deep context for questioning the boundaries and scales of design, questioning things as concrete and ordinary as actual concrete and questioning how we might cultivate new resilience in our practices.

As a designer and artist lacking lab background in biology or chemistry, cultivating and observing microalgae cultures in my home bathroom during a global pandemic ended up not being as tangential to the research as it initially seemed. But before getting into that or how concrete works, its literature, life cycle or further quantifying its impacts, or identifying its low-carbon alternatives, a multi-genre literature review was necessary to appropriately contextualize subjects as massive and complex as concrete and design. From this basis, I began experimentation and material prototyping of low carbon biogenic alternatives to concrete and ceramics which I refer to as Biogenic Cement Composites (BCCs). The prototyping period culminated with the debut of ‘Aperiodic Table’, a bi-modular, reconfigurable sculpture at the 2021 Manetti Shrem Virtual MFA show. Each module is made from a different biogenic cement composite (BCC) formula. Its geometry is based on Penrose tiling, resembling the aperiodic micro-scale aggregate crystallization patterns which occur in cements. Like the periodic table of elements or community quilt projects, it is a multi-phase, collaborative project which artists/scientists will add new BCCs to and reconfigure over time.

Multi-genre Literature Review

Reconciliation Ecology <> Design

The emerging field of Reconciliation Ecology (RE) offers an important transdisciplinary lens for understanding the enormous divide that concrete helps create and maintain between the built and unbuilt world and the environmental and social injustices concrete exploits in the process. Incidentally, RE also offers insights on the disconnect between ecology and design fields which has created an anthropogenic mass that now surpassing Earth's living biomass, why it should concern designers and a framework for how they can begin reconciling it.

Case Study 1: Downtown Austin, Texas- Congress Ave Bridge: Largest Urban Bat Colony in North America

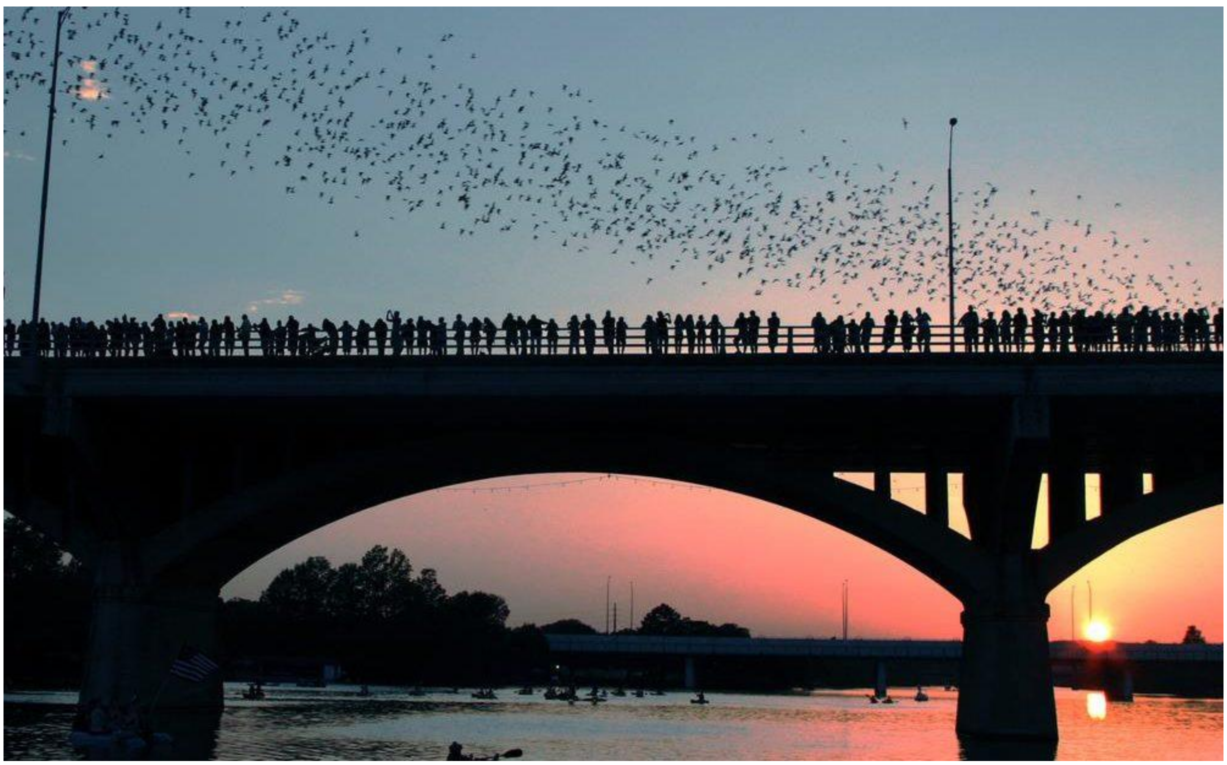


Photo from Austin Monthly Magazine 2017

Before getting into the origins or philosophy behind RE, a quick overview of the Mexican free-tailed bat (Tadarida brasiliensis) of Downtown Austin provides a great working primer on RE in practice.

Originally built in 1910, the Ann W. Richards Congress Avenue Bridge was structurally retrofitted in 1980. Unbeknownst to the design team at the time, the tight crevices between new structural beams were ideal for a migratory bat habitat and were soon occupied. An initial public petition to have the bats eradicated prompted Bat Conservation International (BCI) to start a local campaign to educate the public about bats, emphasizing that bats are gentle, intelligent, and misunderstood creatures that pose no threat to the city or human health. In fact, bats help control insect populations, pollinate, disperse seeds and are an important natural indicator of healthy ecosystems.

Today there are approximately 1.5 million bats that inhabit the bridge and surrounding area, annually consuming thousands of pounds of insects including mosquitoes and agricultural pests, preventing vectors for disease and enhancing the overall ecology and biodiversity of the city. Their nightly takeoff has become one of the most unique tourist attractions in the world and is responsible for over $10 million in annual economic activity. Beyond ecological and economic terms, the bats have assumed an important role in the culture of Austin and its unique civic identity. BCI has since partnered with The Texas Department of Transportation on a project called “Bats & Bridges” to perfect the adaptation of bridges for bat habitation across the state in order to improve bat migration patterns.

Film still from Austin's Nocturnal Neighbors: The Bats of Congress Ave Bridge. BCI 2016

While this introductory case study happens to only focus on one species and not biodiversity at large and doesn’t yet emphasize the inclusion of biogenic materials in the built environment, it clearly demonstrates the ‘bridge’ that RE is trying to form between anthropogenic habitats and what’s left of the natural world. Another, more macro level way to envision this bridge is through this diagram by former UCD ecology professor Michael Rosenzweig and the founder of ‘Reconciliation Ecology’ (RE).

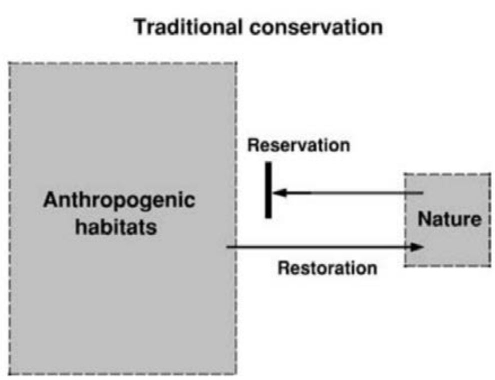


Fig. 5 Conservation’s two dominant strategies, reservation and restoration, view the world as divided into two sorts of areas: natural set-asides and places ruined by the activities of people. Reservation prevents further areas from becoming degraded. Restoration returns areas to the high quality pool.

From ‘Reconciliation ecology and the future of species diversity’, Rosenzweig 2003

The design oversights of Ann W. Richards Congress Avenue Bridge and this diagram both demonstrate the simultaneous need for better bridges and cohesion between designers and ecologists if biodiversity (including our species) is to persist into the next century. As a designer interested in this effort, I am compelled to effectively retrofit this diagram into a new tool. Before that can happen, we need to put Rosenzweig’s diagram into the context of the rest of his work and thinking as well as the context of preceding practices of RE.

Origins of Reconciliation Ecology:

Indigneuous People of past and present throughout Earth are the originators and masters of cultivating biodiversity *in places where people live, work and play* and it is clearly reflected in their design beliefs and practices. Basket weaving is one such practice that, as Tim Ingold observes:

> [produces something that] ...is not 'made' in the sense in which we normally understand the term. Nor, evidently has it grown of its own accord. Thus neither of the available alternatives seem to work for the basket. It does not fit our stereotype of the artefact, and it is not a life-form."

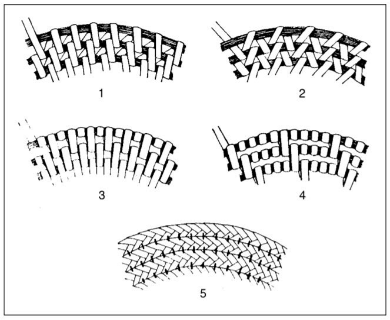


Figure 18.1 Patterns of wrapping in coiled basketry: (1) plain; (2) figure-of-eight ('Navajo'); (3) long and short ('lazy squaw'); (4) Peruvian coil; (5) sewn coil.

From H. Hodges, *Artifacts: an introduction to early materials and technology*, published by Duckworth, 1964, p. 131.

From 'The perception of the environment: Essays on Livelihood, Dwelling and Skill',Ingold 2000

This lack of clear delineation between artifact and life-form or Nature and the Anthropogenic was once characteristic of the entire geography of human settlement across North America. Charles Mann, author of 1491: New Revelations of the Americas Before Columbus, describes Native Americans as having no precept of 'the wilderness':

> Rather than domesticate animals for meat, Indians retooled ecosystems to encourage elk, deer, and bear. Constant burning of the undergrowth increased the numbers of herbivores, the predators that fed on them, and the people who ate them both. Rather than the thick, unbroken, monumental snarl of trees imagined by Thoreau, the great eastern forest was an ecological kaleidoscope of garden plots, blackberry rambles, pine barrens, … spacious groves of chestnut, hickory, and oak.

The fact that there are Native American Lands now known as 'reservations' painfully underscores our misunderstandings and shortcomings of reservation ecology and segregation as a strategy of conservation biology (species conservation). The diagram below is an iteration of Rosenzweig's diagram, adapted to illustrate Native Americans' practice of conservation in response to the 'Settler Colonialism' described by Mann & Dunbar-Ortiz aka 'Anthropogenic habitats'. There is a clear inversion that takes place between our present condition and practice as described by Rosenzweig and what Native Americans practice. Nature dominates and the word 'Reservation' and its accompanying thick vertical line take on new meaning. They are positioned to 'resist' proliferation of anthropogenic habitats rather than to prevent Nature from encroaching upon Anthropogenic habitats.

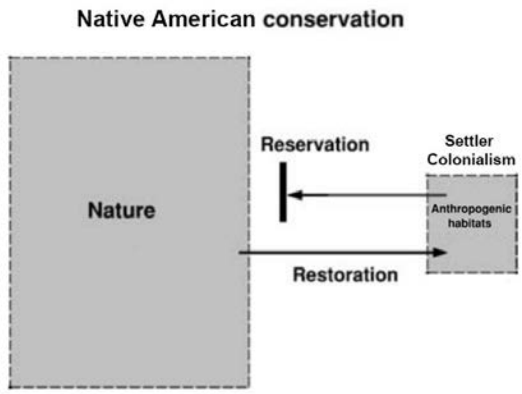


Diagram adapted from 'Reconciliation ecology and the future of species diversity', Rosenzweig, based on 'An Indigenous Peoples' History of The United States', Dunbar-Ortiz, 2014

> "Today's dominate strategy of conservation biology is reservation ecology: save the Earth's natural habitats. However, in many environments, we have already saved about as much natural habitat as we can. A secondary conservation strategy; restoration ecology, supplements reservation ecology. Restoration ecology tries to return some developed places to a more natural status. But the truth is that even less land remains available for restoration than for reservation. The shortage of land turns out to be a critical problem. Because of it, most species, even those apparently now succeeding in our reserves, will eventually vanish. So we cannot rely on the current balance of conservation efforts. Conservation biology must develop a new strategy if it is going to extend and preserve its successes." (Rosenzweig, 2003)

With that opening paragraph to *Win-Win Ecology: How The Earth's Species can survive in the midst of human enterprise*, Rosenzweig introduced 'Reconciliation Ecology' as a new strategy for conservation biology meant to work in concert with 'Reservation' and 'Restoration' practices. Hence the continued alliteration with the word 'Reconciliation' which is also intended to honor its conservation counterparts and their creators.

Rosenwieg's rationale for RE is rooted in his extensive work in the mathematics and science of Species Area Relationships (SPARS). SPARS underscore that biodiversity, or more specifically, the number of species inhabiting an allotted area, is inextricably linked with the size of the area and area type. The larger the area, the more habitat types there are and that is coupled by the fact that all species have restrictive habitat requirements that prevent them from taking over an entire allocated space. In short, area size has a dramatic effect on speciation and extinction rates. The smaller the area size, the more prone it is to a shrinking number of species over time. So when Rosenzweig describes the shortage of land as a critical problem in his opening paragraph, this is what he's referring to.

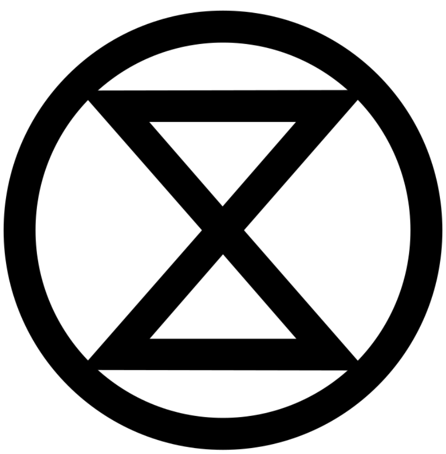
Meanwhile, our area of anthropogenic habitats, or to use design terminology, what Richard Buchanan and Herbert A. Simon would refer to as the area of 'the artificial', increases along with our population and lifespans, reiterating that "conservation philosophy, science and practice must be framed against the reality of human-dominated ecosystems, rather than the separation of humanity and nature underlying the modern conservation movement."(Western)

Modernism & Artificiality vs. Reservation & Restoration:

Western’s words, which inspired Rosenzweig, can be further understood from the standpoint of design and the proliferation of modernism and artificiality and their impact on both anthropogenic and non-anthropogenic habitats. Modernism as a general multi-disciplinary movement embracing the rapid advance of the industrial revolution and breaking from historical styles and traditions has much to do with the modern conservation movement. Aside from contributing to the need for conservation, they both have problematic approaches to the missions they assign themselves. When it comes to architecture, there is no shortage of architects who take issue with modernism. In fact, architect William McDonough even gave a sermon about it:

> “We made glass buildings that are more about buildings than they are about people. We’ve used the glass ironically. The hope that glass would connect us to the outdoors was completely stultified by making the buildings sealed. We have created stress in people because we are meant to be connected with the outdoors, but instead we are trapped. Indoor air quality issues are now becoming very serious. People are sensing how horrifying it can be to be trapped indoors, especially with the thousands upon thousands of chemicals that are being used to make things today”(Design, Ecology, Ethics and the Making of Things, McDonough, 1993)

More generally speaking, both were inherently segregational, exclusionary and reductivist, which were very much aligned with the industrial revolution and the proliferation of division/subdivision of labor, knowledge and specialization which also aligned with a human population boom. Given these circumstances, it is no surprise that designers never significantly engaged in reservation or restoration ecology. It should also come as no surprise that reconciliation ecology today is now so dependent upon effective design work and coordination. Preventing mass extinction requires design work to do more than produce “this generation’s peace sign” (Rose,2019) in the promotion of reconciliation ecology.



‘The Extinction Symbol’, ESP, 2019

From This Moment Despair Ends and Tactics Begin, Banksy, 2019

Preventing mass extinction requires what architect Robert Venturi describes as:

> “an architecture of complexity and contradiction…[one that] has a special obligation toward the whole: its truth must be in its totality or its implications of totality. It must embody the difficult unity of inclusion rather than the easy unity of exclusion. More is not less.”

While he was more likely referring to social, cultural and economic integration at the time, Venturi outlines a sensible approach to ecological integration both for designers and reconciliation ecologists. Venturi goes on to cite authors Christopher Alexander and August Heckscher in his 1966 Complexity and Contradiction in Architecture:

> " 'At the same time that the problems increase in quantity, complexity, and difficulty they also change faster than before. '(Alexander) and require an attitude more like that described by August Hecksher: 'The movement from a view of life as essentially simple and orderly to a view of life as complex and ironic is what every individual passes through in becoming mature. But certain epochs encourage this development; in them the paradoxical or dramatic outlook colors the whole intellectual scene...Amid simplicity and order rationalism is born, but rationalism proves inadequate in any period of upheaval. Then equilibrium must be created out of opposites. Such inner peace as [humans] gain must represent a tension among contradictions and uncertainties...A feeling for paradox allows seemingly dissimilar things to exist side by side, their very incongruity suggesting a kind of truth.' " (Heckscher)

While Venturi rejected Modernism, he and Heckscher point out that it was a necessary step in our maturation as a species to get to where we are now. Moreover, its oversimplification, minimalism and transparency accurately highlight and document all its other deficiencies, making it much easier to adapt and augment with additional layers of life and complexity. So now that we are here, we shouldn't expect former industrial buildings to be converted into wildlife sanctuaries instead of microbreweries or coworking spaces and be successfully populated by diverse wildlife overnight. Instead, we should expect complex issues of compatibility, lifestyles, special needs, public health and that "although these habitats would not be ideally suitable for wild things, they would provide enough support to allow them to adapt to us. They would give natural selection the time and space in which to work, and thus could save the overwhelming majority of today's species" (Rosenweig, Win-Win Ecology, pg 8) Let's also expect that with that time, space and work, we humans can adapt to wild things as well.

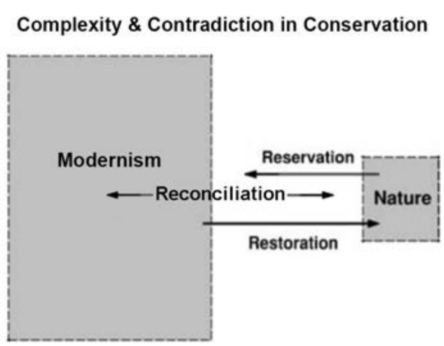


Diagram adapted from 'Reconciliation ecology and the future of species diversity', Rosenzweig, based on 'Complexity & Contradiction in Architecture', Venturi, 1966

Volunteerism <> Citizen Science <> Participatory Design:

Both design and ecology have had no shortage of interested volunteers which have been cultivated and formalized into their respective fields of Participatory Design (PD) and Citizen Science (CS) by way of the internet and social media. PD & CS seem like a critical point of convergence as long-term “[RE projects] will rely heavily on the participation of … citizens and that a model is needed to facilitate public participation and support and to create an evidence base to determine their effectiveness” (Francis, Lorimer). Moreover, in the face of mass extinction, difficult decisions are likely to come up that will require use of such a participatory and democratic model.

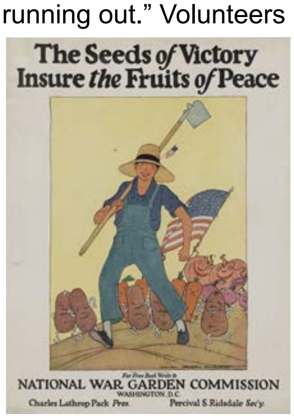
Backyard Wildlife Habitat Sign, National Wildlife Federation, 2003

City of Sacramento public sign, Sutter’s Landing Regional Park, 2019

It seems quite daunting, maybe enough to make Venturi second guess. However, such efforts are well preceded by the Victory Garden efforts throughout WWI, the Great Depression and WWII.

> During 1943, some polls reported that 3/5ths of Americans were gardening, including Vice President Henry Wallace, who gardened with his son. That same year, according to some estimates, nearly 40% of the fresh fruits and vegetables consumed stateside were grown in school, home and community gardens. In addition to providing much-needed food, gardening helped Americans unite around a positive activity. Gardens gave Americans a way to offer service to the nation, enabling citizens on the home front to make significant contributions to the war effort. (Hayden-Smith, Rose. Victory Gardens: Past & Present)

We are currently in the midst of a similar global effort to mitigate a threat that closely resembles a world war. Author Naomi Klein claims it “changes everything”. It involves opposing ideologies, global refugees, mass destruction, famine, fallout, rapidly emerging technologies and a race toward devastation that ultimately results in mass extinction. Call it whatever you will but as London street artist ESP put it: “time’s running out.” Volunteers and gardeners of all species are welcome.



Victory Garden Poster, Maginel W. Barney, 1919

Honey Bee Haven Sign, Pesticide Action Network, 2019

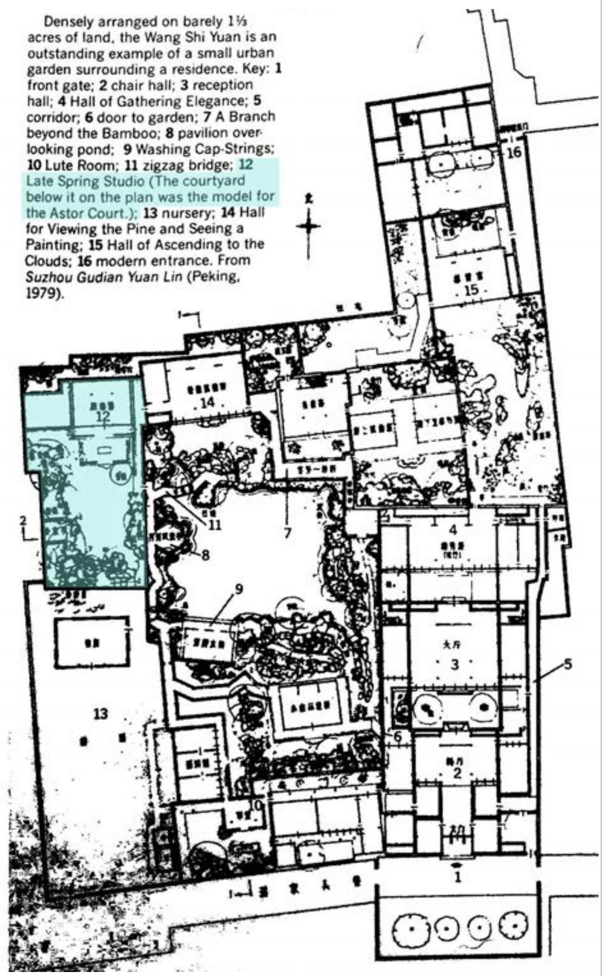
Traditions Informing Concrete's Use in the Built Environment

Like the 'overview effect' that astronauts describe as a shift in global consciousness after viewing Earth from outer space, Elhacham, Et al.'s research marks a fundamental shift in planetary and material consciousness. Their confirmation that humanity's anthropogenic mass now surpasses Earth's biomass also corroborates Reconciliation Ecology's emphasis on mass-cultivation and reconciliation of biodiversity throughout the concrete-hungry anthropogenic habitat if we are to maintain Earth's biodiversity alongside human and planetary health. Toward this objective, it is also important to consider how geodiversity, habitat diversity play into humanity's conceptions of nature and landscape and define our historic obsession with stone which has culminated with the unsustainable rate of concrete consumption.

Case Study 2: Astor Court at The Metropolitan Museum of Art

Within Frederick Law Olmsted and Calvert Vaux's 843 acre Central Park, on the second floor of the Met's Asian Art Galleries, Astor Court was installed in 1981 as part of the first permanent cultural exchange between the United States and the People's Republic of China**.** While Olmsted and Vaux "are credited with coining the term 'landscape architecture' " (Adams, 2009), Astor Court provides a compelling counterpoint to Central Park and a different look at how landscape architecture can be defined and regarded within the built environment, in relation to the unbuilt environment and ultimately peoples' internalized conceptions of landscape and materiality.

Modeled after a courtyard within the monumental Wang Shi Yuan- Garden of the Master of the Fishing Nets- in Suzhou, Astor Court was meant to recreate the multi-faceted experiences and elements of one of Chinese history's most treasured 'Scholar Gardens'. Wang Shi Yuan was originally built during the 12th century by Shi Zhengszhi and originally named Yu Yin- The Fisherman's Retreat. Shi Zhengszhi was the first of several government officials/scholars to reside at this particular garden/home as building gardens was a common past-time of government officials in need of retreat from the rigors of court and public life. "To live as a hermit even in the middle of a marketplace, enjoying a better view that you would have from nesting in the trees." (Murck, Fong, 2012) is an excerpt from *Yuan Ye*- a 1634 treatise on gardens written by Ji Cheng that captures the sentiment at the time.



(Wang Shi Yuan-Garden of the Master of the Fishing Nets in Suzhou, Murck, Fong, 2012)

Government officials of this era are interchangeably referred to as scholars since classical/Confucian literary scholarship was the primary training and prerequisite for serving as a government official. For these scholars, designing, building and cultivating a garden was akin to cultivating oneself and one's connection to the natural world, incidentally this was a major theme in Confucian literature that these scholars had devoted their lives to. It influenced their design sensibilities and literary references were often made throughout the naming and themes of gardens and buildings like Wang Shi Yuan rather than naming them eponymously as is the case of Astor Court.

Scholar Gardening was taken very seriously as an ongoing, lifelong practice that also included meditation, painting, poetry, calligraphy, eating, drinking, various ceremonies and celebrations, and articulating the landscapes, spaces and furniture that these activities would require. While often places of solitude, these places could also be regarded as cultural institutions which supported local economies and ecologies, employing a broad array of builders, craftspeople and artisans with officials acting as the primary designers. One of the most unique, iconic and influential practices to arise out of scholar gardens was stone appreciation and the collection of Gongshi - Scholar Rocks.

Rock/stone appreciation in Chinese history begins at the base of its mountains and along its rivers. Murck & Fong describe “Many of China’s mountains [as] limestone formations that rise abruptly without preparatory foothills. Their imposing height and ruggedness earned them reparations as places of concentrated natural forces - lighting did string them more often - and magical powers. Thought to be the homes of immortals, mountains were considered sacred in their own right. China’s worship of nature, with mountains and rivers as the central focus, spawned an iconography almost as rich as that of Buddhism.” (Murck, Fong, 2012, including photo to upper right)

These folk beliefs would find rich expressions across literature that regarded rocks as “bones of the earth”, paintings that depicted rocks as worlds in and of themselves to be cerebrally explored by viewers, and ultimately gardening and Gongshi which would refine aesthetic principles that would also apply to landscape and design. The Met’s World of Scholar Rocks Exhibition states that “By the Tang dynasty (618–907), four principal aesthetic criteria—thinness (shou), openness (tou), perforations (lou), and wrinkling (zhou)—had been identified for judging scholars' rocks as well as the larger examples featured in gardens.”

Upon exploring Astor Court myself and closely examining several scholar rocks, I felt an unexpected introspective connection to nature that did not require a vast variety of landscapes, vegetation, wildlife or even being outdoors. The pastoral, picturesque and formal landscapes of Olmsted and Vaux's Greensward vision for Central Park outside were all taking place at once, within, and throughout this compact interior courtyard and along the various surface textures and crevices of the scholar rocks. At the time, I was just about to start my first year of architecture school at Pratt Institute and was not yet aware of the literary, design and environmental implications of the historical juxtaposition taking place between Astor Court & Central Park surrounding it.

Red Friend (Portrait of a rock)
Lan Ying (1585-1664), Hanging scroll, ink on paper

Revisiting and comparing Central Park and Astor Court in a longer, broader context of North America's ongoing effort to maintain the competing needs of built and unbuilt environments brings up the importance of peoples' access and relationships to each.

In his 1844 essay *Nature*, Ralph Waldo Emerson writes:

> "At the gates of the forest, the surprised man of the world is forced to leave his city estimates of great and small, wise and foolish. The knapsack of custom falls off his back with the first step he takes. Here is sanctity which shames our religions and reality which discredits our heroes. Here, we find nature to be the circumstance which dwarfs every other circumstance and judges like a god all men that come to her."

Much of American thought on environment and landscape is rooted in Emerson's transcendentalist beliefs about finding god directly and individually in nature, or more precisely-- in undeveloped lands that were uninhabited by non-native peoples, away from cities, towns and colonial settlement. These beliefs were later adapted by his follower Henry David Thoreau who believed that nature should be present in the built environment, as "little oases of wildness in the desert in the city of our civilization" and underscoring nature as a means to restore one's health, spirits, inspiration, and/or faith. When juxtaposing Chinese literature, gardening, architecture and stone appreciation practices with Emerson and Thoreau, there are commonalities in seeking solitude and the end goal of experiencing the sublime through nature. Scholar gardens even do resemble Thoreau's "little oases" in the city but there is not the same sense of "wilderness" to them nor is there a sense of frontier or underlying colonizing occupation. Scholar gardens and scholar rocks are miniaturizations / microcosms for the same landscape-based meditation that lead to the same end goal. This is best explained in comparison to the famed words of John Muir: "By going out into the natural world, I am really going in". Scholar gardens and scholar rocks provide similar introspection relative to the natural world without needing to leave the anthropogenic habitat.

This introspective connection to nature persists today in various ways. Closely examining our consumption, emissions and waste streams with the same awe and principles as Muir, Thoreau, Emerson, and Ji, is key to understanding and maintaining our relationship and interdependence with the natural world. Like stone appreciation, it is a practice that can inform our transitioning to circular economies which can begin to restore our planetary health, natural resources, and the complex biodiversity that maintains and ensures life on Earth. Moreover, looking and working at the micro-scale and with microbes is an effective means of identifying opportunities to design and build with what we currently consider waste in our built environment with negative emissions rather than continuing to extract from the unbuilt environment and combust in the process in order to maintain the built environment. Biocementation is one such example of how this work is being done today. But to properly demystify biocementation, there are more facets to American evolution of landscape architecture, environmentalism and land-use to be explored first and situate it within.

Case Study 3: Hòn Non Bộ at The Balboa Park Botanical Building

In 1870, San Diego passed a law specifying that a 1400 acre area of land "be held in trust forever by the municipal authorities of said city for the purpose of a park", making it the second city in the United States to dedicate a large park following New York City's Central Park in 1858. Originally known as City Park, the land was primarily an open space preserve with various public facilities sprinkled throughout. Starting in 1910, the San Diego business and real estate development community began preparing for the opening of the Panama Canal which would situate San Diego as the closest U.S. Port of Call for vessels headed through the new canal intended to accelerate global trade. The primary preparation would be utilizing City Park to host a World's Fair which would come to be known as the 1915 Panama-California Exposition and require a renaming/rebranding of the park. 'Balboa Park' was the winning entry and homage to Vasco Núñez de Balboa, the first European to pass through the Isthmus of Panama and reach the Pacific Ocean.

Botanical Building & Lily Pond, present day photo from balboapark.org

Utilization and adaptation of the park in response to major global events and influences continues to this day including the Great Depression, WWI, Pearl Harbor & WWII, and the proliferation of international drug trafficking which was narrated in the 1995 Bruce Springteen song entitled ‘Balboa Park’. The Botanical Building was also featured in the 2000 Steven Soderbergh film ‘Traffic’. Throughout this evolution, which included construction of a Navy Medical Center and other military training and housing facilities, the Botanical Building & Lily Pond have persisted as a centerpiece of the park since their completion for the 1915 Expo. Led by planner/architect Bertram Goodhue, and designed by associate architect Carleton Winslow with landscape design by Kate Sessions and Lloyd Wright, the Botanical Building was originally intended as a temporary monument for the Expo similar to the Eiffel Tower for Paris’ Exposition Universelle of 1889 and the Ferris Wheel for Chicago’s World Columbian Exposition of 1890.

Just like the Crystal Palace for London’s Great Exhibition of 1851 before them, these Expos and their unique monuments were each intended by their host city as momentary engineering feats of their industrial and economic might that would fuel further investment and development in their cities. They each showcased new technological and material advances in iron, steel, glass, electric lighting, and reinforced concrete. They were also clearly intended as investments and celebrations for the hyper-advancement of modern global colonization. The 1915 Panama California Expo is unique however, in that it chose botany as its main attraction rather than a manufactured glass, iron or steel monument like its predecessors. The design team opted to build one of the largest open air wooden lath structures in the world, fill it with over 2100 species of plants and surround it with a lily pond and Spanish Colonial Revival architecture which was regarded as vernacular architecture for the region at the time. Given the timing, It stands to reason that the National Parks and conservation efforts advanced by John Muir, President Theodore Roosevelt and others were an influence on this cultural shift in the Expo hosting strategies. President Roosevelt did attend the Expo in 1915 as did President Taft, Henry Ford and Thomas Edison. It also stands to reason that the Panama Canal itself, though over 3700 miles from the Expo, could be regarded as the new engineering feat that easily bested the Ferris Wheel, Eiffel Tower and Crystal Palace combined, thus permitting such an unorthodox, horticultural-centric World Expo centerpiece. The Botanical Building holds its own against its Expo predecessors in that it was beloved by visitors during its Expo and still is to this day.

The Panama Canal was formally opened on August 15, 1914, four months before the start of the Expo, as the largest American engineering project to that date. It required 5 million cubic yards of concrete, excavation of 232,353,000 cubic yards of earth and 5609 lives were lost during just the American phase of construction (The canal began as a project of France)(Panama Canal Museum). The American Society of Civil Engineers designated The Panama Canal as one of the "Seven Wonders of the Modern World and a Monument of the Millennium." (ArmyEngineers.com) For a point of comparison, the Hoover Dam which would begin construction later in 1933 required 4.36 million cubic yards of concrete and excavation of 5,500,000 cubic yards of Earth.

Construction of locks on Panama Canal, 1913, Library of Congress cph.3c25093

Both the Panama Canal and the Botanic Building are in operation today and have continually been expanded upon. One of the most unique recent additions to the Botanic Building is Phan Văn Lit is Hòn Non Bộ work. As enscripted in the plaque below the work, 'Hòn Non Bộ' directly translates from Vietnamese to English as : Hòn - Island, Non - Mountain, and Bộ - a combination of water, mountain range and forest, or it can also mean "imitating the way the scenery looks in miniature".

A native of Vietnam, where he was a nationally regarded horticulturalist specializing in cactus and succulents, Phan moved to the United States in 1980 and settled in San Diego in 1983. He is a leading historian and practitioner of Hòn Non Bộ credited with introducing it to American audiences via horticultural exhibitions. Working for the City of San Diego Parks Department, he has also managed the Botanical Building and Balboa Park Desert Garden for many years.

Hon Non Bo in Balboa Park's botanical garden, 2000. Photo by Michael Liu, Flickr

In describing the history of Hòn Non Bộ, Phan begins by pointing out that, like Gongshi in China, Hòn Non Bộ originates from ancient Southeast Asian and Vietnamese peoples' worship of stones and that they "also prayed to spirits of rivers, trees and mountains. They believed there were sacred spirits in mountain caves who built mansions in a paradise to isolate their sacred world from the human world. People made an effort to enter this sacred world so they never die. It was not possible for all people to live near a cave in the mountains, so they created in their own homes a Hòn Non Bô containing water and stones set together to look like islands in the ocean with mountain ranges and plants."

Like China, Australia and other places with long histories of rock animism, Vietnam is home to many inselbergs or monadnocks, "island mountains" or more specifically dramatic rock and mountain formations that appear to arise suddenly from the landscape or bodies of water. In addition to being considered sacred and mystical, these geographical features have special roles throughout Vietnamese history, culture, identity that influence its built environments and place-making which can be well demonstrated and explored in the appreciation and creation of Hòn Non Bộ.

Hang Gio Dong (East Wind Cave) at Ngu Hanh Son (Five-Element Mountain), Central Vietnam. Photo by Nguyet-Mai Dinh

Panorama of Uluru at sunset (Uluru is also known as Ayers Rock) Central Australia. Photo by Stuart Edwards

In addition to Hòn Non Bộ, Phan is an accomplished Bonsai practitioner and points out interesting distinctions between the two traditions and ultimately how both can be regarded as constructing apertures for viewing and knowing the greater world and universe.

> In the philosophy of Japanese bonsai, Heaven is at the top of the tree, Man is represented by some point in the middle branches and Earth is at the bottom branch. The three points form a scalene triangle, one whose sides are all of different lengths. In Hòn Non Bô, the points are interpreted very differently. The top is Natural (heaven equaling the sky, clouds, stars, moon) rather than a mythical heaven. The lower section is Earth (represented by soil, water and mountains) and Man is between the Natural/heaven and Earth. In fact, the person building Hòn Non Bô, or the people walking around looking at Hòn Non Bô, represent Man. The Chinese letter for "heaven" also means "Natural." Thus it is accepted that man carries on his head the Natural (heaven) and has his foot touching the ground or Earth and that the Natural, the Earth and Man are the same One.

While these are ancient practices that may be considered subjects of Traditional Ecological Knowledge (TEK), following these philosophies and continuing these practices today can transcend new scales and serve as aids in re-examining the current states of the built and unbuilt environment and our relationships with each. This is best demonstrated by Gongshi and Hòn Non Bô work's ability to "borrow views" (Ji, 2012) from their surrounding landscapes to augment viewers' perception of their greater surroundings, such as in Dam Sen Park Saigon (see photo below). So for the Botanical Building, now a public parks facility, to be managed by someone like Phan and to host a permanent Hòn Non Bô work as well as temporary Hòn Non Bô, Bonsai, Gongshi exhibitions and others that that foster community around garden appreciation practices is a remarkable adaptation of "the [original] purpose(s) of a park" (see page x) and of a former monument to modern colonization.

Large Hòn Non Bô in Dam Sen Park (demonstrating "borrowed views"). Saigon, Vietnam. Photo by Nguyet-Mai Dinh

In comparing Hòn Non Bộ to the Panama Canal, like comparing Astor Court and Central Park, differences in scale are obvious but lead to compelling facets. The Panama Canal set the tone for the 20th century in terms of what could be built and how the world would come to depend on concrete and thus limestone and sand. Such leaps would define the 20th century built environment. The scale, scope, logistics and complexities of the monumental project required major innovations across many disciplines that all ultimately led to more material, more distance, more energy and more work all done in less time. We have accelerated this trend ever since and per Pascal Peduzzi's research and many others', it is leading to "massive impacts on the planet and thus on people's lives" (see pg 14). As researchers and industries adapt to emerging circumstances like climate change and attempt to start a new green industrial revolution for the 21st century, or rather a circular revolution, microbiology and microecology have emerged as areas of increasing interest. Designer, researcher and biocementation specialist Damian Palin explains why in his paper entitled *Radical Means: Materials and Manufacturing Technology Inspired by Nature:*

> Given their profound effect on modern day geochemistry, ecology, and their ubiquitous presence, it is reasonable to assume that, at a time when microorganisms were the only life form on the planet, they must have had a huge impact on shaping the biosphere. With this in mind it is also logical to postulate that microorganisms could have a similarly profound effect – on the economics of the manufacturing industry, with the potential for radically reduced energy consumption and environmental degradation – providing key insights as to how we can create and evolve radical production methodologies inspired by nature.

Palin's insights are corroborated by the fact that one of the biggest obstacles to the construction of the Panama Canal was the spread of Malaria and Yellow Fever. Subsequently, two of the most radical design innovations behind the Panama Canal were the discovery by Major Ronald Ross that these diseases were transmitted via parasites and viruses in mosquitoes and the following enactment of a holistic seven point mosquito abatement plan led by Drs. Gorgas, LePrince, and Darling that would save countless lives

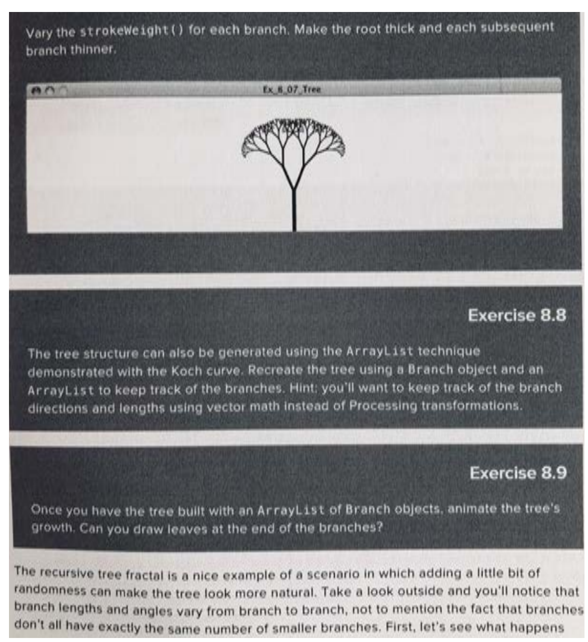
(CDC, 2017). Palin's insights are further underscored by the current Covid 19 Pandemic occurring at the time of this writing.

Hòn Non Bộ and similar miniature landscape/waterscape cultivation practices can go beyond isolated labs to share valuable observations and insights on the cultivation of micro-climates and micro-ecosystems which can assist in the "[creation, recreation and evolution] of radical production methodologies inspired by nature." In other words, miniature landscape practices offer a means of holistic ecological observation, experimentation and prototyping that include creative and cultural dimensions to the work, along with broader participants and audiences.

Miniature landscape practitioners and stone enthusiasts are well poised to be early, impactful adopters of microbial driven materials like biocementation, bacterial cellulose, and mycelium, providing new data and insights as artists and citizen scientists. Like biodiversity itself, this degree of interdisciplinarity is fundamental to facilitating transitions to more circular, mutual and resilient systems and relationships throughout the built environment. Likewise, it is critical for art & design schools to begin transitioning to these materials and practices as design tools and creative mediums. Architectural models, site models, design prototypes and art projects should not be reliant on fossil fuels and destined for landfills or digital archives when their material life cycles can directly assist in efforts like carbon sequestration, topsoil regeneration, resource/waste recovery/diversion and/or ecological restoration. Moreover, if the prototyping and modeling cannot be done in this manner, how can the final project ever hope to be? This is the first and perhaps hardest step in the process of truly transitioning to a more circular built environment.

The purpose of comparing these different projects has been to highlight the ways in which built environments and their design depend on the non-human world and processes in more ways that we know, and how critical it is to re-examine the human builders' roles and means in maintaining both the built and non-built world. As the last century/millenia has been defined by pushing outward and discovering how big we can make things, our recent technological advances have been defined by how small we can make things and rely on us looking inward. While miniature landscape practices are a reminder of this, nowhere is this more readily apparent than our reliance on electronics and digital computing in contemporary life - in the specific minerals, materials, and manufacturing and planned obsolescence they require - and ultimately in the virtual and social realities they foster.

The amount of time people are spending indoors and in front of device screens (even independent COVID restrictions) and reducing their access to biodiversity and geodiversity, or nature, is at a point that Muir, Ji,Thoreau, Emmerson, or the Olmsteads could have never imagined. Incidentally, and also in response to this, design practitioners have taken to computational design methods with biomimetic and biophilic intentions of creating what architect Neri Oxman describes as "design inspired nature". Meanwhile, computer programmers and educators like Daniel Shiffman advocate for creative coding practices as a form of recreation that diverts from orthadox computer science education. Doing so increases literacy and awareness of coding principles alongside the system dynamics at play behind many natural systems. His book, *Nature of Code* is prefaced with these questions:


Vary the strokeWeight() for each branch. Make the root thick and each subsequent branch thinner.

Ex_8_07_Tree

Exercise 8.8

The tree structure can also be generated using the ArrayList technique demonstrated with the Koch curve. Recreate the tree using a Branch object and an ArrayList to keep track of the branches. Hint: you'll want to keep track of the branch directions and lengths using vector math instead of Processing transformations.

Exercise 8.9

Once you have the tree built with an ArrayList of Branch objects, animate the tree's growth. Can you draw leaves at the end of the branches?

The recursive tree fractal is a nice example of a scenario in which adding a little bit of randomness can make the tree look more natural. Take a look outside and you'll notice that branch lengths and angles vary from branch to branch, not to mention the fact that branches don't all have exactly the same number of smaller branches. First, let's see what happens

Tree structure exercise using the Koch curve. pg 380 excerpt from Nature of Code, Shiffman

How can we capture the unpredictable evolutionary and emergent properties of nature in software?

How can understanding the mathematical principles behind our physical world help us to create digital worlds?

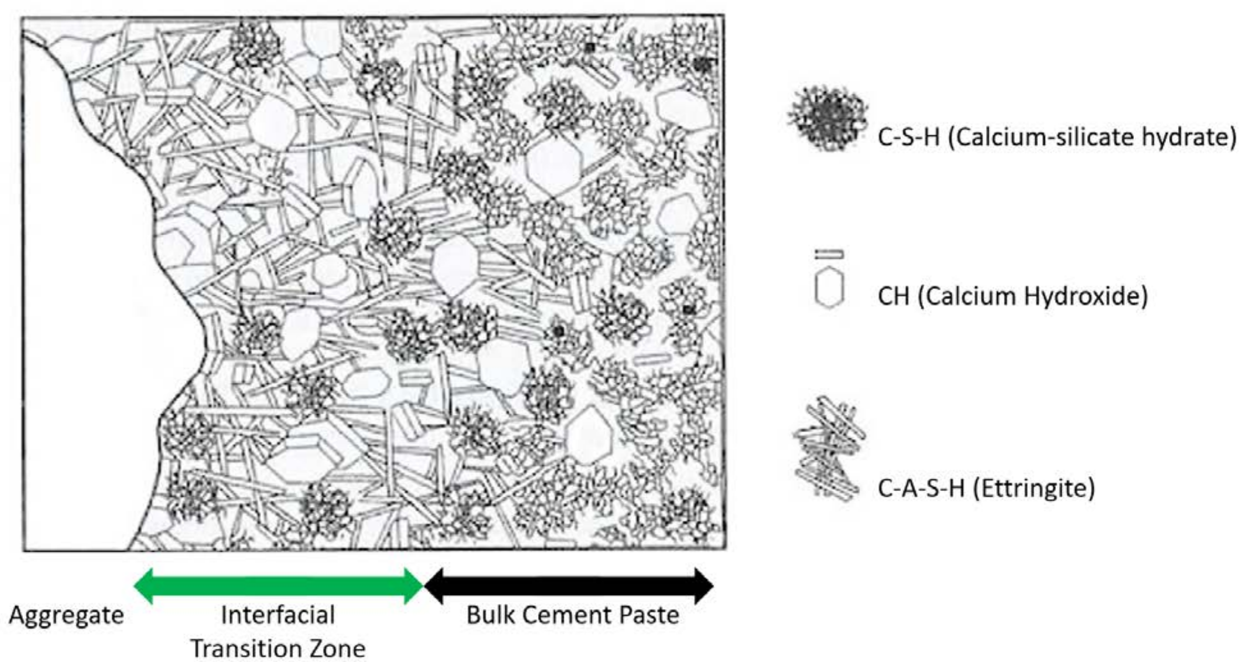
It is exciting to see how these questions and exercises can be tempered with miniature landscape practices like Gongshi and Hòn Non Bộ as they pose very similar questions each in their own right. Moreover, just like these ancient practices have adapted to new countries, materials and audiences, I am also excited to see how they will be augmented by current and emerging digital technologies in addition to biotechnologies like biocementation as they present an ideal scale and accessibility for prototyping. Observing the proliferation of terrariums, succulents, air plants, living walls and even climbing walls in common, domestic and high-tech workspaces offer reasons to be optimistic as do Phan Văn Lit is adoption of digital fabrication, electric water pumps and misters to create active water features in his Hòn Non Bộ work. This intersection may appear trivial but stands to produce tools of transition that may greatly influence and affect changes across design philosophies, materiality and the built environment.

Concrete’s life cycle <> Microbially Induced Calcite Precipitation (MICP)

The force of the ordinary . . . can be obscured, reduced, or eliminated . . . by a lack of appreciation of the richness of its connections to the larger world it composes. -Thomas Dumm

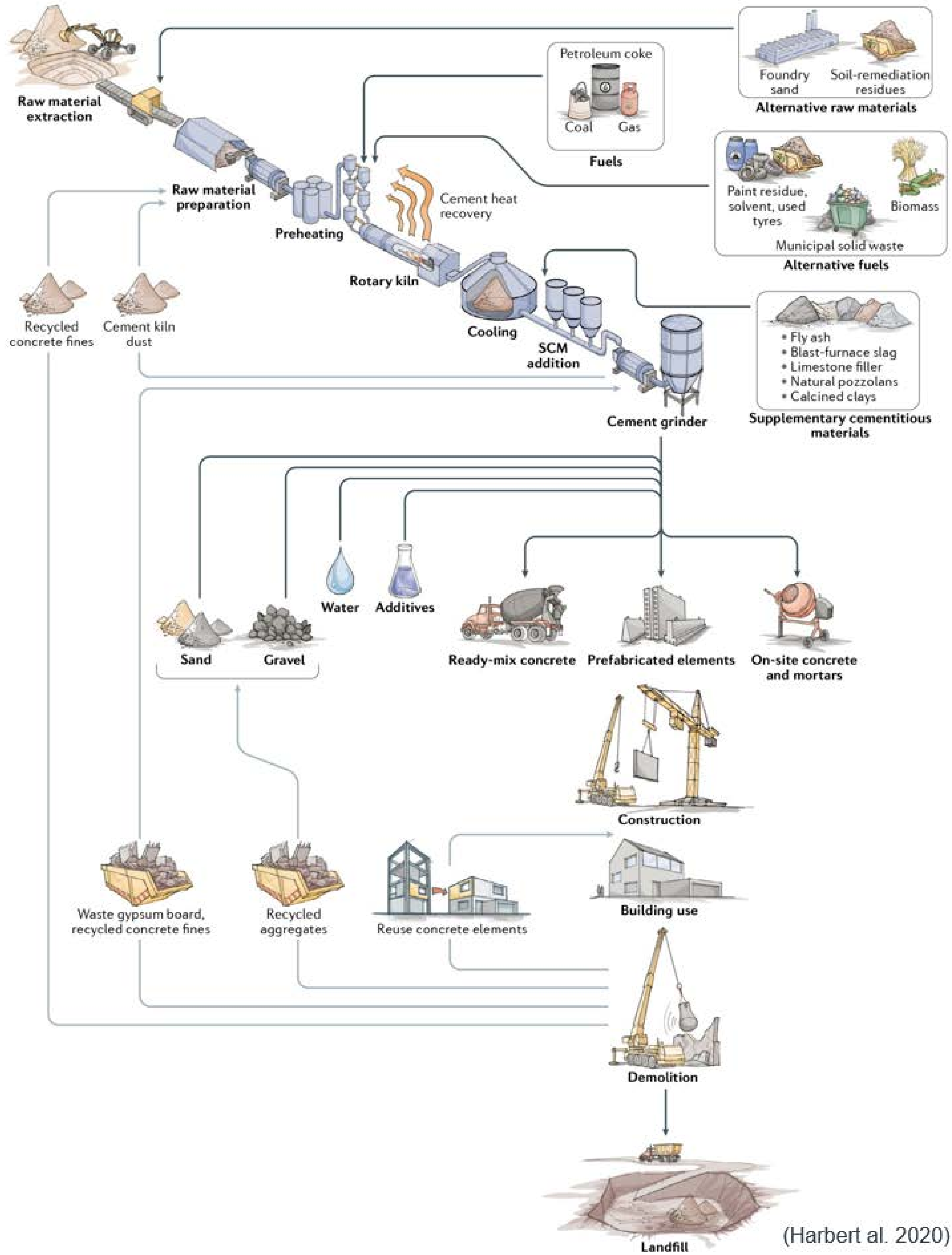
“Nobody knows exactly when humans first discovered lime. Perhaps ancient occupants of Earth used limestone rock to protect their fireplaces. Fire heated the rocks and the first burnt lime was created. It then rained and the lime slaked into calcium hydroxide, which reacted with the ashes and sand around the fireplace creating the first ancient mortar.” (LHOIST.COM)

While dramatic rock formations (non-anthropogenic and anthropogenic alike) continue to universally inform and inspire peoples’ sense of Earth, ferity, fertility, nature, nation, place, aesthetics and now computation, concrete is most often experienced, understood and underappreciated as an ordinary, and uniform background material. Yet any closer look at a concrete reveals a world of information as demonstrated with Beiser’s 2018 book title “The World in a Grain: The Story of Sand and How it Transformed Civilization”. Up close to the naked eye, dramatic grain-sized rock formations (aggregates) appear beneath the uniform surface to start telling the story of concrete. With the aid of microscopy, even smaller calcium-silicate hydrate, calcium hydroxide, and ettringite crystallizations appear between the aggregates, binding them in place.



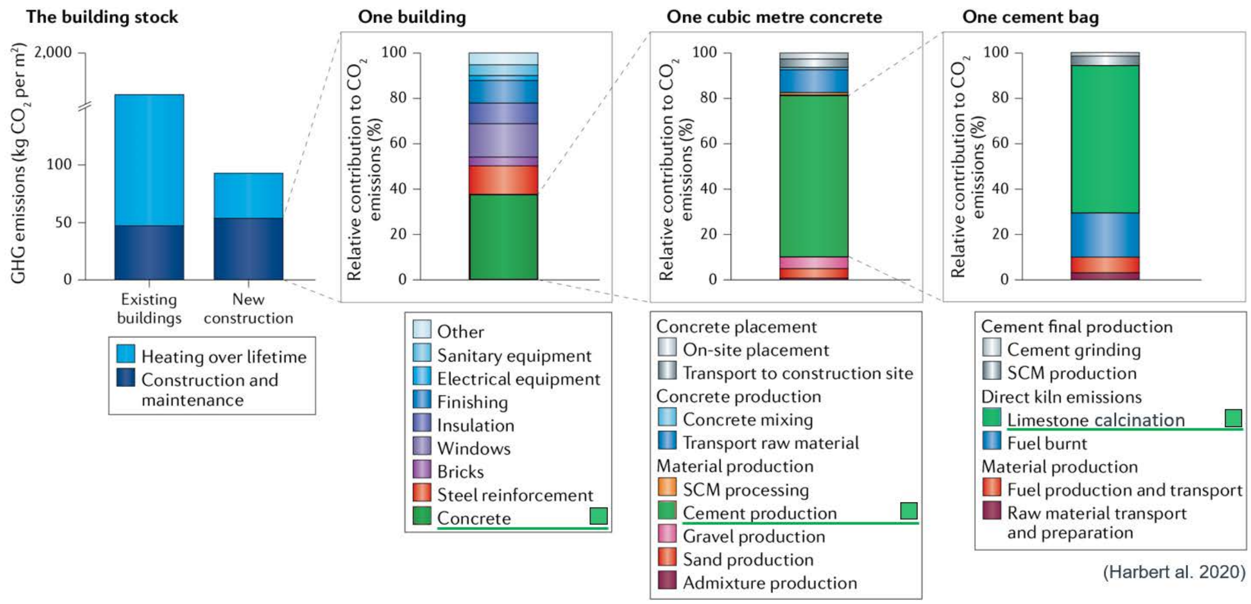
Sabbie Miller, UC Davis, Cement Composites Lecture, 2020

Pulling back to take a look at where these aggregates and binders come from reveals a complex, energy and emissions intensive industrial production life cycle where various different materials are "aggregated", heated, prepared and transported into the final uniform material. Chief among these materials is the 50 billion tonnes of sand per year that makes sand the second most consumed natural resource on Earth after water. (pg 1)



(Harbert al. 2020)

Surprisingly, this massive amount of sand production/transport only represents less than 4% of the emissions associated with the full life cycle of concrete. It is cement production that is responsible for the bulk of emissions despite accounting for typically 1/6 the mass of sand required in typical concrete production.



(Harbert al. 2020)

The graph above illustrates how concrete emissions represent 38% of the relative emissions associated with the construction of a typical building. Cement production accounts for 70% of concrete emissions. Within the realm of cement production, is the primary emitter: Limestone calcination. It accounts for 65% of cement production emissions. In other words, the initial one-time limestone calcination reaction during the manufacture of the cement needed for a typical building accounts for 17% of its construction and maintenance emissions.

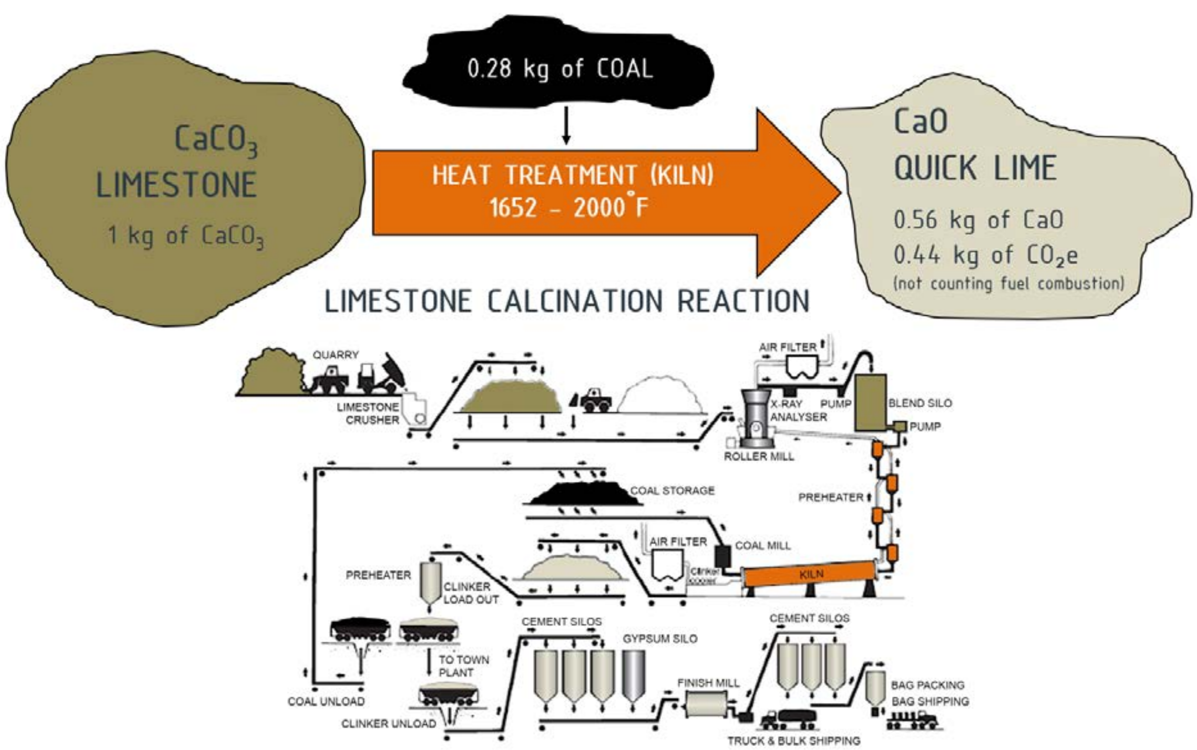


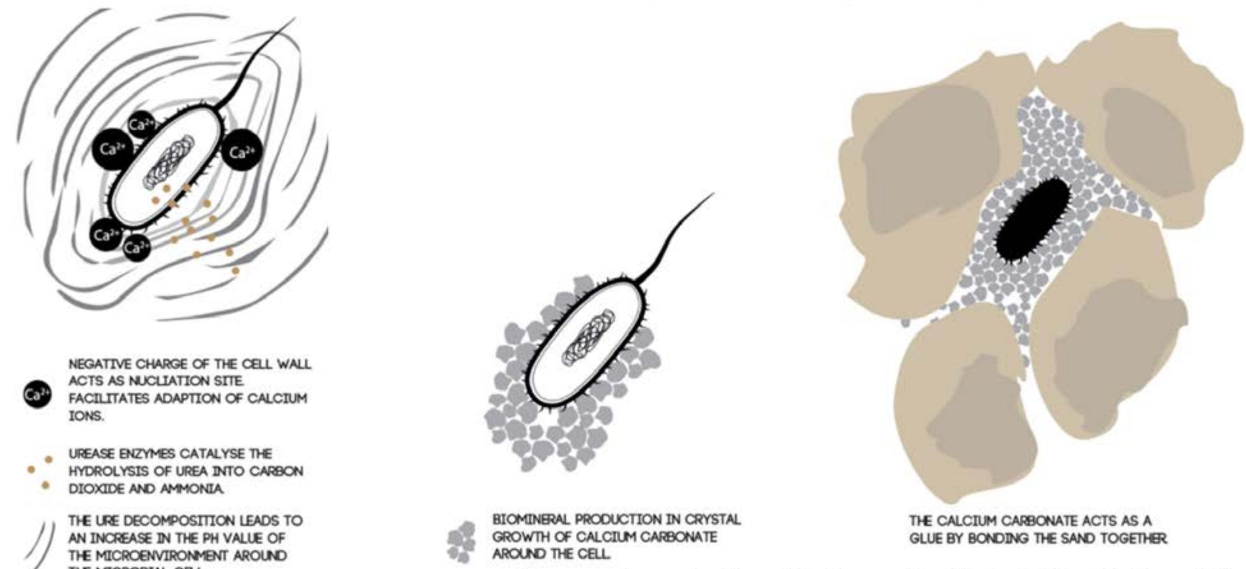
Diagram adapted from UC Davis Cement Composites Lecture Slide, Sabbie Miller, 2020

Much like fossil fuels, limestone ($CaCO_3$) inherently contains sequestered carbon. The process of limestone calcination involves quarrying it, crushing it and then applying prolonged intense 1652-2000℉ heat in order to produce calcium oxide (CaO) or quicklime, a key component of cement that makes the crystal formations of calcium-silicate hydrate, calcium hydroxide, and ettringite possible. Unfortunately, these temperatures cannot be sustained with the energy density of renewable energy sources. They require higher density fossil fuels. Regardless of required fossil fuel-based emissions throughout the quarrying, crushing and heating of the limestone, the majority of CO_2 emissions from limestone calcination come from the carbon sequestered in the limestone source itself. For every 1 kg of $CaCO_3$ processed, 0.56 kg of CaO is yielded and 0.44 kg of CO_2 is emitted into the atmosphere (see previous diagram). This results in cement production being relatively low-volume yet high-emission within the life cycle of concrete and what American political theorist and philosopher Jane Bennett would refer to as immense *thingpower*: "the curious ability of inanimate things to animate, to act, to produce effects dramatic and subtle" (Bennett, 2004)

Another way to imagine quicklime's *thingpower* is by considering how the approximately 10% of all anthropogenic CO_2 emissions that come from the production of concrete influence the climate crisis. Aside from Bennett's political theory and the United Nations Environment Programme mentioned earlier, there are several others who recognize cement's disproportionate impacts and need to prioritize its decarbonization. In 2021, the California Legislature passed Senate Bill 596 Greenhouse gases: cement sector: net-zero emissions strategy - Becker. The California Nevada Cement Association has also made a concerted pledge to achieve carbon neutrality by 2045 using a strategy of "One Bold Goal. Three Pathways. Nine Levers" detailed in the diagram below. With these new circumstances, new research & development into alternatives to limestone calcination is likely to follow.

MEASURES	Legislative Assistance	Regulatory Assistance	Public Acceptance	Public Funding	RD&D	Supply Limitation
PATHWAY 1: PROCESS EMISSIONS						
Lever 1 **Portland Limestone Cement** (PLC)		●	●			
Lever 2 **Carbon Capture Use & Storage** (CCUS)	●	●	●	●	●	
Lever 3 **Alternate Raw Materials** (ARM)		●	●		●	●
Lever 4 **Alternate Cements & Clinkers**					●	●
PATHWAY 2: COMBUSTION EMISSIONS & FUEL SWITCHING						
Lever 5 **Natural Gas**	●	●	●			●
Lever 6 **Waste-Derived Fuels**	●	●	●			●
Lever 7 **Biomass-Derived Fuels**	●	●	●	●		●
PATHWAY 3: ELECTRICITY GENERATION						
Lever 8 **Waste Heat Recovery**	●	●		●		
Lever 9 **On-Site Renewables**	●	●				

Policy Diagram, California Nevada Cement Association, 2021



Sporosarcina pasteurii precipitation reaction illustrated by T.H. Arnardottir

Microbially Induced Calcite Precipitation (MICP), more commonly referred to as biocementation or biomineralization, presents one alternative to the calcination process that is being actively researched throughout the world, including UC Davis. MICP involves low-impact cultivation and deployment of alkaliphilic microbes to precipitate calcite (calcium carbonate) formations in the pores of an aggregate mix, binding them into a stonelike form similar to cement or concrete without any temperature or pressure requirements. Aside from water & aggregates, there are three primary inputs required for to facilitate MICP (Achal , 2015):

1) Alkaliphilic microbe(s) - Microbes that thrive in high pH environments
2) Substrate Solution(s) - Solutions which provide nutrition to microbes and/or other organisms
3) Calcium Ion Solution(s) - Solutions which provide soluble calcium that can interact microbes

Through a series of complex biochemical reactions in an ambient, high pH aqueous environment, alkaliphilic microbes utilize nutrients from a substrate solution like urea in combination with a calcium ion solution like calcium chloride to initiate MICP within the pores of an aggregate mix similarly to how a conventional portland cement would form Ettringite, Calcium Hydroxide & C-S-H. Moreover, this process is an adapted simulation of how calcium carbonate formations geologically occur in the unbuilt world, taking shape as limestone, sandstone, corals, seashells, nacre, stalactites and stalagmites.

Driven by continued pressures for increased structural performance, cost-reduction, scalability, life cycle sustainability, decarbonization and circularization of the construction industry, biogenic alternatives for each of these inputs are continually explored in scientific research literature.

1) Alkaliphilic Microbe(s)

Sporosarcina pasteurii has emerged to be the predominant alkaliphilic microbe for MICP research, in part due to the works of Magnus Larson and Damian Palin which brought MICP and Sporosarcina pasteurii before broader audiences concerned with climate change mitigation and environmental degradation at large. S. pasteurii is ideal for MICP because it is an aerobic, spore-forming, non-pathogenic, lab-grad cultivated bacteria and has demonstrated a high rate of MICP activity. This is in part due to its replicable compatibility with urea and yeast extract as a substrate and calcium chloride as a calcium ion solution by many different researchers throughout the world.

Compressive strengths of the resulting cementations using this baseline formula range from 334 kPA to 70 MPa across the experiments referenced below. This baseline formula is widely regarded as a baseline control for additional experiments that explore factors like specific applications of MICP cementaitons, the comparative performance of other microbes or biogenic alternatives to substrate and calcium ion solutions. Currently, MICP is used in applications for soil stabilization, concrete crack repairs, fracture sealing of oil/gas wells and bioremediation efforts. The current state of MICP is not on par with the wide performance capability or availability of conventional portland cement across countless applications throughout the built environment.

Synechococcus sp. PC 7002 is a more recent microbe being cultivated and considered for MICP, biogenic cement and more specifically Living Building Materials (LBMs)- materials that are capable of successive regeneration and self-healing over time (Heveran, 2019). As one of the fastest growing photosynthetic cyanobacteria, Synechococcus is of interest for its scalability, capacity for biosequestration of carbon, and capacity for bio-engineering and cultivation to optimize for MICP and other LBM related functions. It also has a longer lifespan than S. pasteurii and currently has a tested compressive strength of 3.6 MPa in its resulting cementations using a “calcium containing nutritional media” (Heveran, 2019) and gelatin.

While alternatives to S. pasteurii are being researched, including the ambient or native bacteria found inhabiting the aggregate mixes being used in cementations, species like Bacillus licheniformis are being considered for use in conjunction with S. pasteurii. Bacillus licheniformis is a common soil bacteria that’s being used in conjunction with S. pasteurii to create nacre (mollusk shell) inspired bacterial composite materials (Spiesz, 2019). Similar to the cross section of plywood or natural nacre, it is used specifically to cultivate alternating layers of polyglutamate “glue” between layers of calcium carbonate precipitated by S. pastuerii to form a “bacterial composite” that structurally outperforms natural nacre (Spiesz, 2019).

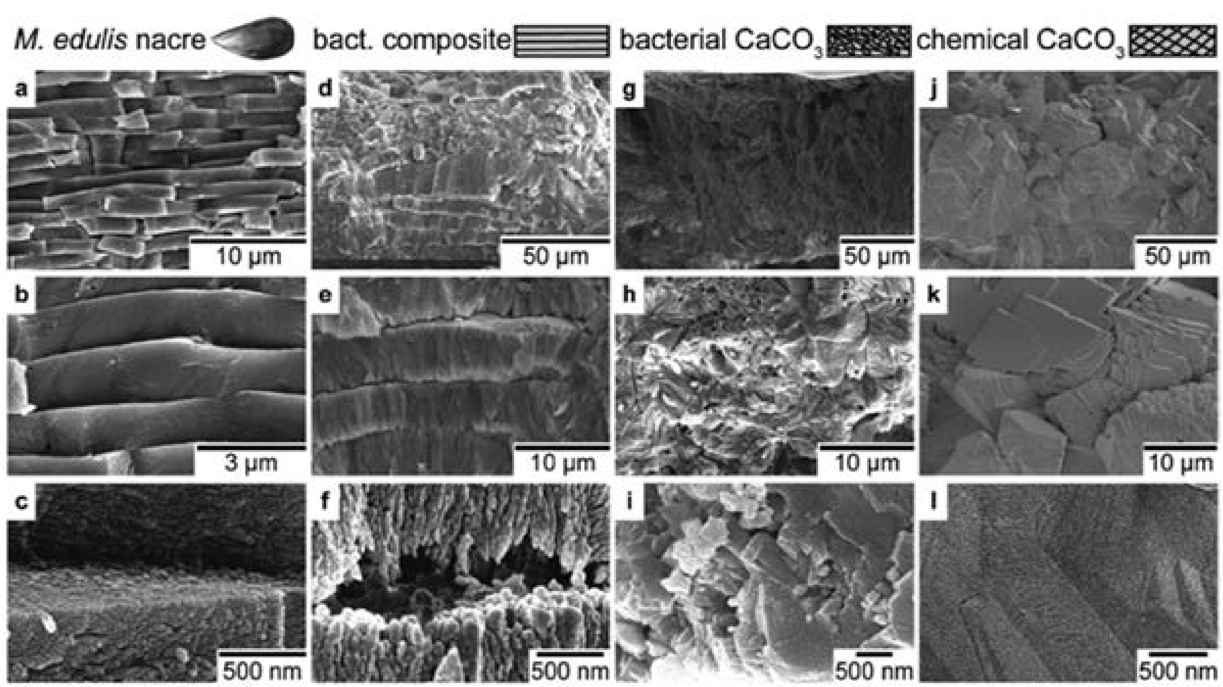


Figure 2. Bacterially produced composite contained calcium carbonate layers similar to natural nacre. Samples were fractured, and cross sections were imaged by SEM. a) *Mytilus edulis* nacre showed a characteristic layered structure with b) layer irregularity enabling interlocking and c) nanoasperities (nanospheric texture) that resist inelastic shearing, both acting as toughening mechanisms. d) Bacterial composite, produced through alternate deposition of calcium carbonate by *S. pasteurii* and submersion in PGA produced with *B. licheniformis*, also displayed e) irregular layers and f) nanoasperities (nanospheric texture), which might contribute to increased toughness. g–i) Bacterial calcium carbonate material produced by repeated deposition with

(Spiesz, Et al. 2019)

Referencing the microscopic images above, the second column in particular, these increases in stiffness and toughness are explained by rougher surface areas meeting each other in between the layers of calcium carbonate and polyglutamate created by their respective microbes. These rougher surfaces greatly increase the surface area of contact between layers, interlocking them almost like velcro layers or a zipper. What's interesting to note in this experiment is that there are no aggregates being cemented in the process. it is compelling to imagine bacterial composites making the need for sand across the built environment obsolete and addressing the complex issues of sand extraction. At the same time, it is also compelling to imagine how this nacre inspired layering technique could incorporate an aggregate mix and further enhance structural performance.

2) Substrate Solution(s)

Urea is the predominant substrate source for MICP. Worldwide global production of synthetic urea was 218 million metric tons in 2019 and projected to reach 301 million by 2030 (M. Garside, 2020). It is primarily used in agricultural fertilizers. Incidentally, urea was the first biogenic chemical in history to be chemically synthesized in 1828 by Friedrich Wohler (Keen, 2005). Biogenic urea is produced in the liver and is many organisms' primary means of nitrogen excretion. It exits the body via urine and has been used widely in fertilizers. If not properly treated or diverted in wastewater treatment plants, large amounts of urea, either biogenic or synthetic, can trigger eutrophication when released in watersheds and the ocean, subsequently producing harmful toxins and oxygen depletion. Incidentally this corresponds with surges of storm water than overwhelm wastewater treatment facilities.

In MICP research, Synthetic lab grade urea powder combined with yeast extract is the predominant source of substrate solution for providing nutrition for Alkaliphilic microbes and S. pasteurii in particular. Synthetic lab grade Urea is highly soluble, has a neutral pH and long shelf life which make it effective for MICP. However, researchers are interested in what alternatively abundant sources of urea can be used or reclaimed to facilitate MICP in place of grade lab urea which can be cost prohibitive and ecologically expensive and exploitive. Sourcing naturally abundant urea can be a key to improving the life cycle and impacts of biocementation based products. More specifically, it could play a key role in mitigating impacts concerning eutrophication and nitrogen management. Moreover, affordable urea sources mean that MICP can be more accessible to a broader group of small scale producers and users throughout the world.

Several research projects involve human urine recovery for MICP. University of Cape Town, South Africa is of particular interest and publicity due to the region's ongoing drought and urine recovery playing a part in their climate adaptation planning (Lambert, Randall, 2019). The process starts with preventing enzymatic urea hydrolysis (EUH) from taking place in fresh urine. During EUH, nitrogen/urea are released as gas with strong odor from the urine before it can even be used in the MICP process. To avoid EUH, University of Cape Town researchers (Lambert, Randall, 2019) experimented with adding calcium hydroxide $Ca(OH)_2$ to fresh urine under the hypothesis that increasing the pH level of typically neutral pH of fresh urine would prevent EUH. They identified that a range of 4.3 to 5.8 grams of calcium hydroxide per liter of urine at 25*C could raise pH to 12.5 and that the maximum pH in which EUH could occur was 11. Lambert & Randall caution that pH is also influenced by temperature and identify a range of 0 to 40*C for maintaining stable urine in addition to a pH range of 11 to 13. Moreover, they recommend 10 grams of calcium hydroxide per liter as an additional buffer.

This biogenic urea from human urine was then used with S. pasteurii, equal parts Cape Flats dune sand and Greywacke aggregate sieved through 0.15mm pores and a calcium chloride solution in an MICP process to manufacture “biobricks” with a compressive strength of 2.7 MPa. Lambert & Randall compare this to a 40% limestone brick strength of 0.75 MPa, a 1.95 MPa compressive strength for a 20% cement brick and a 14.5 MPa compressive strength of a face brick. As mentioned before, this is not yet comparable to the performance of portland cement. Moreover, it is unclear if the treatment of urine with calcium hydroxide, a non-biogenic industrial chemical, ends up being more ecologically and economically costly than using synthetic urea instead. Nonetheless, the experimentation provides a proof of concept for human urine in the production of MICP based cement.

Chicken Manure Effluent, a byproduct of biogas production typically used in agricultural fertilizers, provides a similar alternative to synthetic urea for Yoosathaporn Et al. Additionally, the chicken manure effluent increases S. pasteurii's capacity for MICP and increases compressive strength by 30% (see table below) while reducing substrate cost by 88% and providing waste stream diversion that could have contributed to eutrophication. These compressive strengths are on par with those of conventional portland cements. Looking at the electron micrograph images below, their diverse calcium carbonate formations resemble the composition of Ettringite, Calcium Hydroxide & C-S-H formations found in conventional portland cement as well. Like human urine, chicken manure effluent as a raw biogenic material is highly nitrogenous and widely available. Unlike human urine, chicken manure effluent isn't sterile and is highly microbially active which may explain why it can result in producing more calcium carbonate formations.

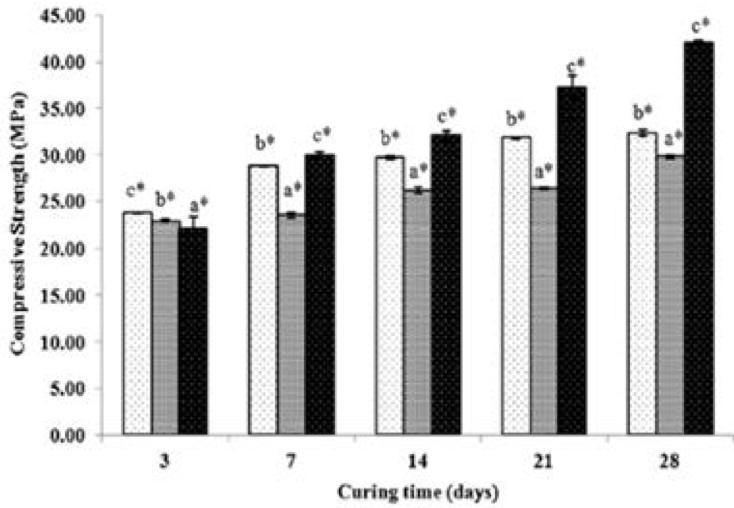


Fig. 4. Effect of B. pasteurii KCTC 3558 on the compressive strength of cement cubes of control (□), CME-urea medium (▩) and B. pasteurii KCTC 3558 cultured in CME-urea medium (■) at 3, 7, 14, 21 and 28 days of curing. *Data represent the average of five independent experiments with standard error bars. English alphabets are a statistical comparison between groups using ANOVA and post hoc Duncan's test. Different letters on each column indicate significant differences among treatments.

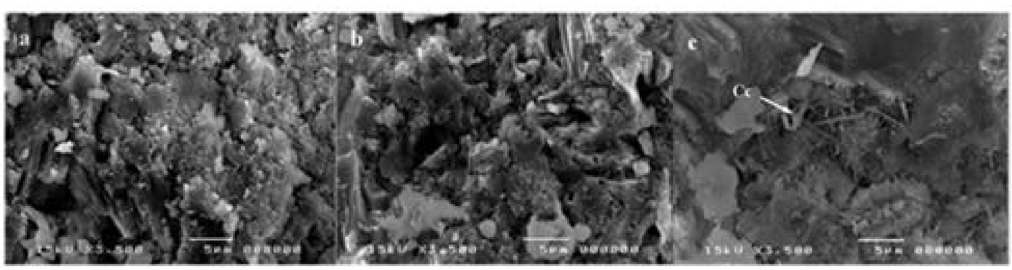


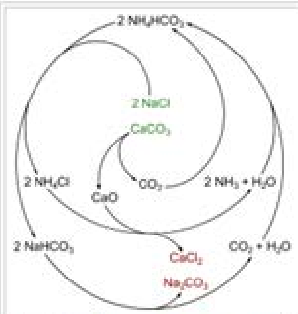
Fig. 5. Scanning electron micrographs of (a) control cement cubes with tap water (b) cement cubes with CME-urea medium and (c) cement cubes with *B. pasteurii* KCTC 3558 cultured in CME-urea medium; showing biocalcification induced by microbes (calcium carbonate crystals were indicated with Cc).

(Yoosathaporn Et al., 2016)

In addition to biogenic alternatives for urea, researchers are also exploring alternatives to the yeast extract that typically accompanies urea as a secondary element in substrate solutions for MICP research. Yeast extract is inherently biogenic but some research shows that yeast extract can disrupt the initial setting of cementations in addition to being cost prohibitive (Amirir Et al. , 2018). Corn Steep Liquor (CSL) is one such alternative to yeast extract currently being explored. Corn Steep Liquor is a byproduct of corn wet-milling operations that is typically used as a feed additive for livestock and in the cultivation of various microbial cultures including Penicillium for the production of penicillin. According to Amirir Et al., CSL provides cost savings and doesn't disrupt or delay the initial setting of cementation like yeast extract does. "Almost 60% of the total operation cost of the Urea Yeast Extract medium is due to use of yeast extract".

3) Calcium Ion Solution(s)

According to research literature, calcium chloride is the most common source for creating Calcium Ion Solutions to be used in MICP. Worldwide, calcium chloride is most widely distributed and used in a powdered form as a deicing agent for seasonal road maintenance. It is also a common staple in a wide range of lab-based research including various applications as pigments and food additives which is likely how it became a standard in MICP lab research.



The Solvay Process as an example of a cyclic process in chemical industry (green = reactants, black = intermediates, red = products)

Test identifier	Calcium source	UCS (kPa)	Permeability (10^{-6} m/s)	Quantity of calcite (%)			
				Top	Center	Bottom	Average
CC-1	Calcium	316	3.82	5.3	4.1	6.4	5.3
CC-2	chloride	291	5.56	5.1	4.3	6.3	5.2
CC-3		360	1.27	6.4	5.1	7.2	6.2
CC-4		370	1.06	6.9	5.4	7.5	6.6
ES-1	Eggshell	392	6.54	7.1	5.6	7.7	6.8
ES-2		418	1.63	8.2	7.0	8.0	7.7
ES-3		404	2.68	8.0	6.8	8.1	7.6
ES-4		335	4.41	7.4	4.4	7.7	6.5

https://commons.wikimedia.org/wiki/User:Sponk

Table. Summary of Testing Results (Choi Et al., 2016)

Calcium chloride is most commonly produced as the primary byproduct of the Solvay process for industrial sodium carbonate production which uses salt brine, limestone and thermal energy as primary inputs. 2005 worldwide production of sodium carbonate was estimated at 42 million metric tons. (Kostick, 2006) Similar to portland cement production, the Solvay process relies on the calcination of limestone. Variations of the Solvay process are being proposed for carbon sequestration (Huijgen Et al., 2003) and calcium chloride byproduct remains abundant, stored in large wastebeds and discharged offshore worldwide; suggesting that it be a scalable input for biogenic cement applications. Calcium chloride also happens to be readily available in the cement/concrete industry as a chemical admixture used as “the best known and most widely used accelerator.” (Metha, 2014) Despite these factors, biogenic alternatives for MICP Calcium Ion solutions are still being explored as calcium chloride poses environmental/soil health problems, cost barriers and harm to concrete in large doses(Choi Et al. , 2016).

Biogenic alternatives may also enhance performance of the resulting biogenic cement as is the case with eggshell derived soluble calcium by Choi Et al. (see table above). Higher levels of calcium in the eggshell solution vs. calcium chloride solutions lead to higher percentages of calcite formation and reduced permeability which result in higher unconfined compressive strength (UCS). Calcite is the strongest of the three molecular crystalline formations, or polymorphs, that calcium carbonate assumes during formation. Aragonite and vaterite are the other two polymorphs which can also occur during MICP.

Eggshells consist of over 94% calcium carbonate and were easily dissolved in generic distilled white vinegar over a three day period by Choi Et al. to create a calcium ion solution that could then be used for MICP experimentation. The vinegar itself could also be considered as a biogenic resource as a product of acetic acid bacteria. As the eggshells dissolved in the vinegar, their calcium carbonate content split into soluble calcium and carbon dioxide bubbles. Urea was then added to the calcium ion solution and applied to the tamped sand samples between applications of an alkalophilic microbe solution which consisted of freeze-dried Bacillus sp. and distilled water.

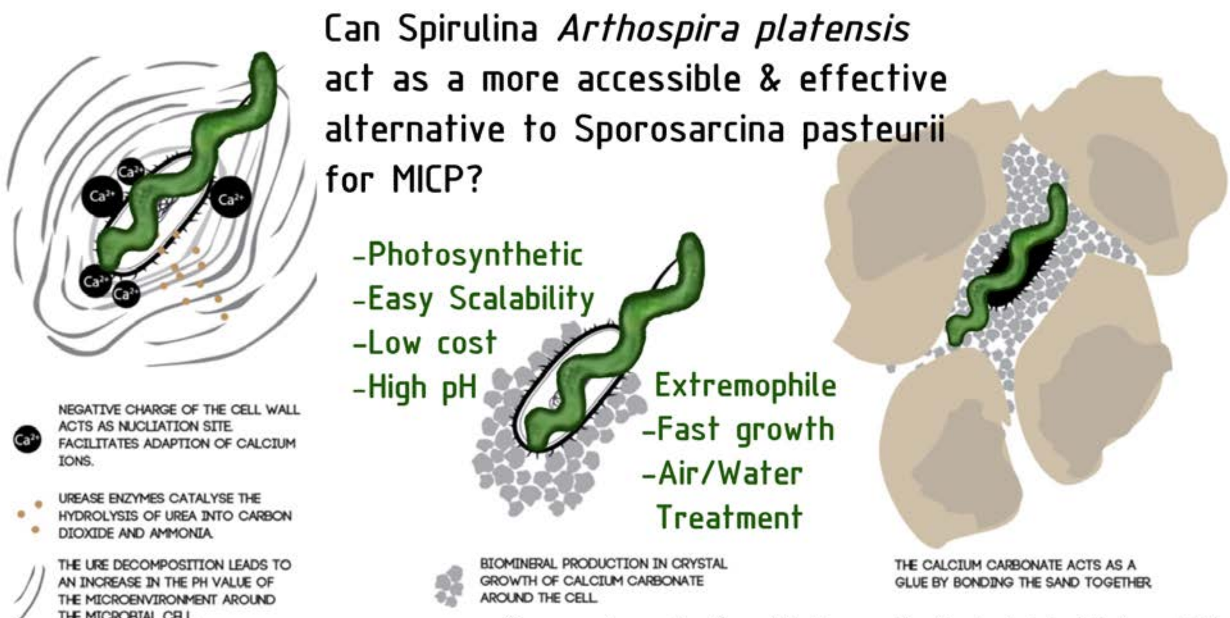
It remains to be determined how Choi Et al.'s experimentation with eggshells address their initial concerns over calcium chloride’s cost barriers or potential harm to concrete and soil health as their testing of eggshell based MICP didn't address these factors. Aside from this, the UCS measurements were very low compared to conventional portland cements and other MICP experiments. This could be explained by several factors. UCS is determined by aggregate specifications, in this case a single mean grain size of 0.42mm was used and not discussed. The selection of freeze-dried Bacillus sp. instead of a live culture might have also influenced UCS but was also not discussed. The inclusion of vinegar, in theory, could have also lowered the pH of the solution and the overall environment for MICP which could have also affected the UCS, permeability and quantity of calcite. Addressing these factors could better inform the comparison between conventional inputs like calcium chloride and biogenic inputs like eggshell derived calcium for MICP. At a more macro-level, it would also be informative to know more about the availability and life cycle assessment of scaling up eggshell derived calcium ion solutions to match the current abundance of calcium chloride and to compare their respective life cycle assessments.

Author	alkalophilic microbe (MICP)	subtrate solution	calcium ion solution	other	biogenic strength	control strength
Choi	Bacillus sp.	urea	eggshell	n/a	387.25 kPA UCS eggshell	Calcium Chloride 334.25 kPA
Gomez	Sporosarcina pasteurii/native bacteria	urea	calcium chloride	n/a	1.9 MPa unconfined compressive strength	n/a
Lambert	Sporosarcina pasteurii	human urine	calcium chloride	n/a	2.7 Mpa compressive Strength of biobrick	0.75 MPa 40% limestone brick 1.95 MPa 20% cement brick 14.5 Mpa face brick
Heveran	Synechococcus sp. PC 7002	only defined as "calcium containing nutritional media"	only defined as "calcium containing nutritional media"	gelatin	3.6 Mpa	3.5 MPa = "minimal acceptable strength for ordinary Portland cement-based mortars"
Spiesz	Sporosarcina pasteurii, Bacillus licheniformis	urea	n/a	Bacillus licheniformis produced polyglutamate (PGA) solution	70 Gpa stiffness , toughness estimated to be 1000x higher than pure aragonite crystal	70 Gpa stiffness for pure calcium carbonate
Yoosathaporn	Sporosarcina pasteurii	Chicken Manure effluent	calcium chloride	n/a	42.13 MPa compressive strength	32.34 Mpa coventional cement control
Khodadadi	n/a	urea	calcium chloride	jack beans (Canavalia gladiata)	UCS: 4 MPA	n/a
Amiri	Sporosarcina pasteurii	Corn Steep Liquor (CSL)	calcium chloride, calcium nitrate tetra hydrate,	n/a	compressive strength at 28 days: Bac_UCSL : 48 MPa Nut_UCSL : 68 Mpa	compressive strength at 28 days: Bac_UYE : 54 Mpa Nut_UYE : 70 MPa

Literature Summary Table

The lack of options for biogenic calcium sources for MICP in the current literature along with the uncertainty of their scalability suggest the need for additional research into post-consumer calcium sources that follow the same intent of biogenic resources to circularize and/or decarbonize the cement industry. The Carpet America Recovery Effort (CARE) incentivizes carpet waste landfill diversion and is developing a market for Post Consumer Carpet Calcium Carbonate (PC4) which contains over 70% calcium carbonate. Along with similar efforts to divert and repurpose post consumer gypsum board and similar calcium carbonate based products, research efforts into their viability as calcium sources for MICP as well as supplementary cementing materials (SCMs) and admixtures could be worthwhile and complementary to biogenic resources. The importance of developing viable post-consumer resources in addition to biogenic resources is now further underscored by Elhacham Et al's discovery of anthropogenic mass exceeding the mass of all living biomass on Earth.

Similarly, complementary research into new alkaliphilic microbes for MICP in addition to S. pasteurii could be worthwhile as was demonstrated by Spiesz, Et al.'s work integrating S. pasteurii and Bacillus licheniformis to create nacre inspired composites, especially as microalgae cultivation is expanding all over the world. Robust, alkaliphilic microalgae like Spirulina and Chlorella are easily grown with minimal inputs and mentioned in MICP literature as having great potential as MICP microbes (Ariyanti, 2012) but have not yet been significantly tested. Spirulina (Arthrospira platensis) is a fast growing, highly photosynthetic microalgae that "pulls 10 times as much carbon dioxide from the air as regular plants." (Schwab 2019) Currently, spirulina cultivation and research and market growth is being driven by a number of applications including human food supplements, livestock feed, cosmetics, medicine, biofuels and carbon sequestration. It requires minimal upfront resource investment (Ramanan Et al. 2010) and is particularly suited for warm climates. Given these circumstances, it stands to reason that microalgae cultivation and its economic development could empower communities in the very places where people and land are being exploited in the extraction of sand for the collosal demand of concrete. Moreover, it is compelling to imagine all the ways that microalgae production facilities could integrate with brickmaking production, cement/concrete production and other related building material manufacturing operations throughout the world. One particular starting question is how can CO_2 emissions from material production be directly channelled to adjacent microalgae production which could then biosequester it.



Sporosarcina pasteurii precipitation reaction illustrated by T.H. Arnardottir

Aside from speculative research, it is important to recognize that soil stabilization has been a major driver for MICP research and provided its first steps into commercialization (Gomez, 2018). This pragmatism addresses MICP's current shortcomings in terms of its overall compressive strength as compared to conventional portland cement. With that in mind, it becomes important to understand and strategize what other pragmatic applications of MICP come next. Calcium chloride is a great example of this as it is already known in industry as the most familiar accelerant for portland cement based concrete. The biogenic MICP materials discussed could be researched as supplementary Cementing Materials (SCMs) in portland cement based concretes that reduce the overall amount of portland cement required. It also stands to reason that Biogenic MICP solutions may also provide a means of pretreatment of new aggregate and post consumer aggregate sources. Aggregates like wind eroded sand and post consumer crushed concrete and glass that don't have optimal surfaces and/or interfacial transition zones in theory could benefit from a MICP pretreatment that might make their physiology more ideal for use in concrete mixes.

In addition to these many physical and technical areas, there are significant social obstacles to biogenic cements that could be better understood. Overcoming "ick factor" or "social legitimacy" is already a common obstacle in the world of wastewater reuse and nutrient recovery (Harris-Lovett, 2015) and is likely to be an obstacle for any products that are derived from human urine. This is underscored by our current public health crisis with COVID-19. If we are to fully address decarbonization and circularization across our built environment and economy, "ick and social legitimacy factors" must be much more holistically researched and understood in order to be overcome in addition to continuing to make the necessary incremental technical advances for such a transition.

Cultivation & Iteration with Biogenic Cement Composites

It turns out that we are only 10 percent human: for every human cell that is intrinsic to our body, there are about 10 resident microbes — including commensals (generally harmless freeloaders) and mutualists (favor traders) and, in only a tiny number of cases, pathogens. To the extent that we are bearers of genetic information, more than 99 percent of it is microbial. And it appears increasingly likely that this "second genome," as it is sometimes called, exerts an influence on our health as great and possibly even greater than the genes we inherit from our parents. But while your inherited genes are more or less fixed, it may be possible to reshape, even cultivate, your second genome. -Michael Pollan

Like the NASA Astronauts and Elhacham, Et al.'s anthropogenic mass research, Michael Pollan's words describe another fundamental shift in consciousness and worldview. Thinking at this scale of the microbial world and human microbiota, rather than global-scale shifts, reveals humanity's most direct, intimate and most ancient connections to the living world. It is an important continuation of Reconciliation Ecology thinking with the human body being the epitome of "the anthropogenic environment" that now dominates Earth's biosphere and land area. At the same time, the 10:1 influence that non-anthropogenic microbiotic life has on human life and human biomass is also underscored. This immense mutualism throughout the microbial world and the human microbiome blurs delineation between the built and unbuilt environment and between Earth's anthropogenic mass and living biomass, providing further relevant insights into concepts like thingpower and traditions like rock/landscape animism, Gongshi and Hòn Non Bộ.

With these points in mind, and COVID restrictions, I modified my own home-studio to include cultivation and prototyping with biogenic cement composites (BCCs) as low-carbon alternatives to making sculpture with concrete and ceramics. The practice weaves the preceding multi-genre literary research with hands-on skill building and material experimentation, starting with attempting mutual relationship building with microbes. Or as Bruno Latour would put it with "collaboration" with microbes rather than their cultivation. In this way, I've also come to regard this home-studio adaptation as an ongoing reconciliation ecology project in my own home. In other words, my family took on billions of new housemates. The studio practice consisted of weaving four major ongoing activities that culminated with a bi-modular, reconfigurable sculpture that debuted at the Manetti Shrem Museum's 2021 MFA show.

1) Microalgae Cultivation
2) Mixing Aggregates
3) Casting Composites
4) 3D Printing Composites

Before detailing these activities, it is important to define BCCs and compare them to Microbially Induced Calcite Precipitation MICP. MICP is a specific process facilitated by alkaliphilic microbes that results in the formation of calcite between different aggregates, binding or 'cementing' them together into an overall stone-like form. BCC is a term that applies to the broader inclusion of biogenic or bio-based materials throughout a cement composite's constituents, not just as an alternative to cement. For instance, BCCs include bio-based alternatives to sand-like aggregates, not just the constituents of cement. Hempcrete, which combines conventional calcined limestone as a binder and biogenically derived hemp hurds as an aggregate could be considered a BCC. Tabby concrete, which utilizes calcined oyster shells as a binder and crushed oyster shells as an aggregate could also be considered a BCC. Typical cement based concrete using conventional sand and gravel aggregates and no biogenic material would not be considered a conventional cement composite and not a biogenic cement composite. BBCs support the objective of decarbonizing concrete and cement as their biogenic material content sequesters atmospheric carbon and in best case scenarios, they reduce reliance on extraction of sand and limestone and limestone calcination.

1) Microalgae Cultivation

For the practical and hypothetical reasons discussed on pg 30, I selected Arthrospira platensis ‘Spirulina’ as the single alkaliphilic microbe to be researched. While it would have been great to compare Spirulina-based composites and Sporosarcina pasteurii-based composites in a university lab setting, COVID restrictions required a work from home approach, making a singular focus on spirulina more plausible. I found an in-state supplier of spirulina and nutrient solutions, Algae Research Supply in Carlsbad, California that was accustomed to supporting many home-growers of spirulina who grow it as a dietary supplement and fish feed in aquariums. Eventually, after trying several locations, I adapted my bathroom to accommodate approximately 7 gallons of spirulina cultures that would be injected as an aqueous solution in various BBC trials. This involved basic aquarium implements: heaters, a plant propagation heat pad, an aquarium air pump, tubing, airstones, glass vessels and supplemental overhead lighting. Lighting cycle duration, Lighting intensity, aeration intensity, temperature, pH level, and nutrient/mineral inputs were the major parameters that are being continually optimized.

Home bathroom microalgae cultivation

As a designer and artist lacking lab background in biology or chemistry, cultivating, observing and utilizing spirulina cultures in my home bathroom during a global pandemic was an unprecedented experience that incited unexpected thinking that was not as tangential to the research as it initially seemed. An experience that I imagine other designers, artists and citizen scientists at large would benefit from trying. Moreover, it is an experience that may eventually become more commonplace throughout the built environment and the home. As I was regularly reconfiguring the setup, monitoring the cultures, watching them get greener and greener and harvesting, I was reminded of the home bathroom’s history and how its role has been ‘recast’ from time to time: being used for alcohol production, as blackrooms for photography, as recording studios for musicians, etc. In my case with spirulina cultivation, I found it compelling and uncoincidental that conducting material research into decarbonizing the built environment and making art with more ecologically responsible materials ended up including a multi-functional adaptation of my own built environment. Adaptations that enhanced its ecology, resilience, self-sufficiency and building performance as 7 gallons of spirulina provides a great thermal mass and “pull[s] 10 times as much carbon dioxide from the air as regular plants”. Moving forward, I hope to incorporate CO_2 meters in order to quantify the system’s impacts on indoor air quality over time.

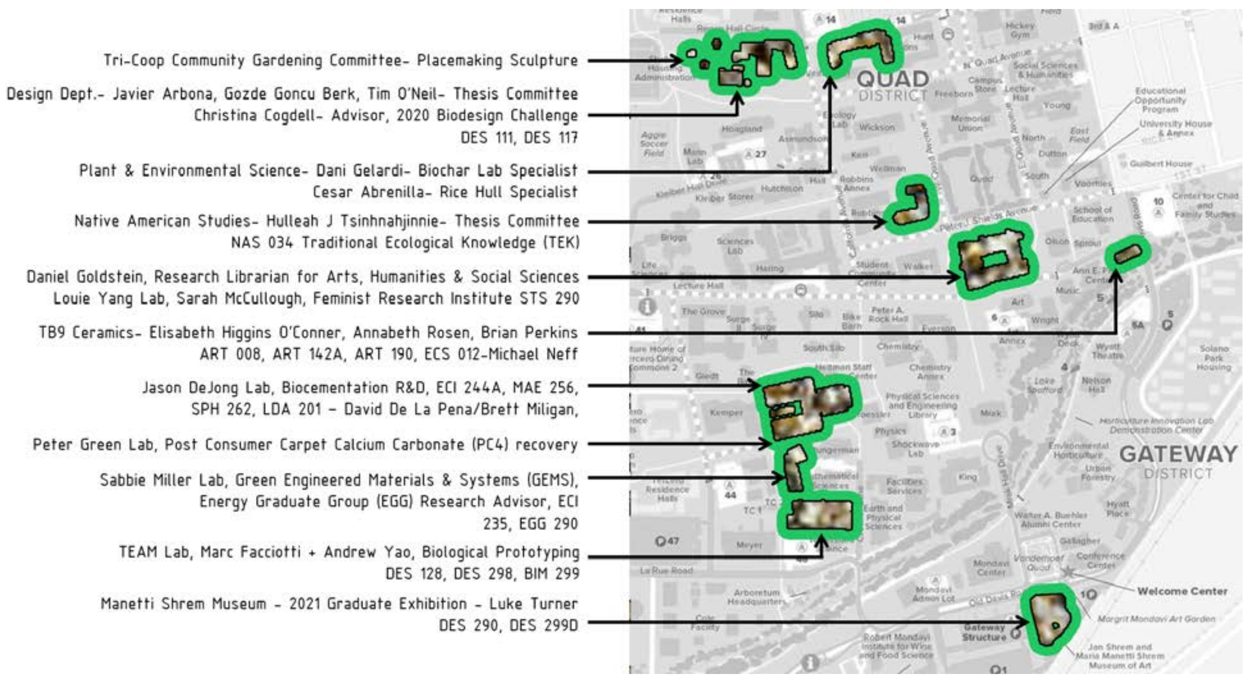
Modifying my bathroom also underscored the importance of adaptable modularity, site and living conditions in designing and conducting experiments and research. I would later discover that living where/with your work/subject and the spatial multifunctionality that is involved are important aspects of the design of field stations and space stations where some of the most important research on climate and various other topics takes place. Had I conducted this research from a typical university lab setting as initially planned, I might not have gained the same perspective and insights that have proven invaluable to my ongoing studio practice and home.

Glass vessels as bioreactors

Aside from these spatial, contextual takeaways, observing and interacting with the spirulina itself on a daily basis had a familiar impact on me. Watching live video feeds of free floating spirulina from a USB microscope, I was reminded of the scholar rocks in Astor Court (pg 11) and how it was possible to connect with the natural world, to the Earth, without isolation in “wilderness”, wildlife or even being outdoors. As an avid gardener, I quickly came to regard spirulina cultivation in the same light as Gonshi, scholar garden culture or Hòn Non Bộ. It is a common remark by gardeners, farmers, Hòn Non Bộ and Bonsai practitioners and horticulturalists at large that cultivation is mutual: plants cultivate us as we do them. It is further underscored by Michael Pollen’s writing about our “second genome”. I embraced this belief and relied on it to temper the many new technical aspects and technological skillbuilding like constantly leveling the beds of my newfound 3D printers and manually modifying g-code for digital fabrication. Moreover, it is my hope that despite a lack of hard data, these kinds of qualitative observations and practices can be of service to the advancement of science communication and interdisciplinary relationship building.

2) Mixing Aggregates

BCCs are marvelous mediums for aggregating knowledge from fields of study and industries as well as aggregating different materials that might otherwise be considered waste within a single industry. In aggregating concerns about reconciliation ecology, the global imbalance between anthropogenic mass and living biomass and impending sand shortages in addition to the decarbonization of concrete, this project prioritized sourcing post-consumer, post-industrial, and biogenically derived minerals and aggregates. The project title “Recasting Resilience” refers to how the typical roles of these materials and the larger roles of waste and industries might all be ‘recast’.



Map of multidisciplinary aggregation

Post Consumer Carpet Calcium Carbonate (PC4) aka ‘Carpet Powder’

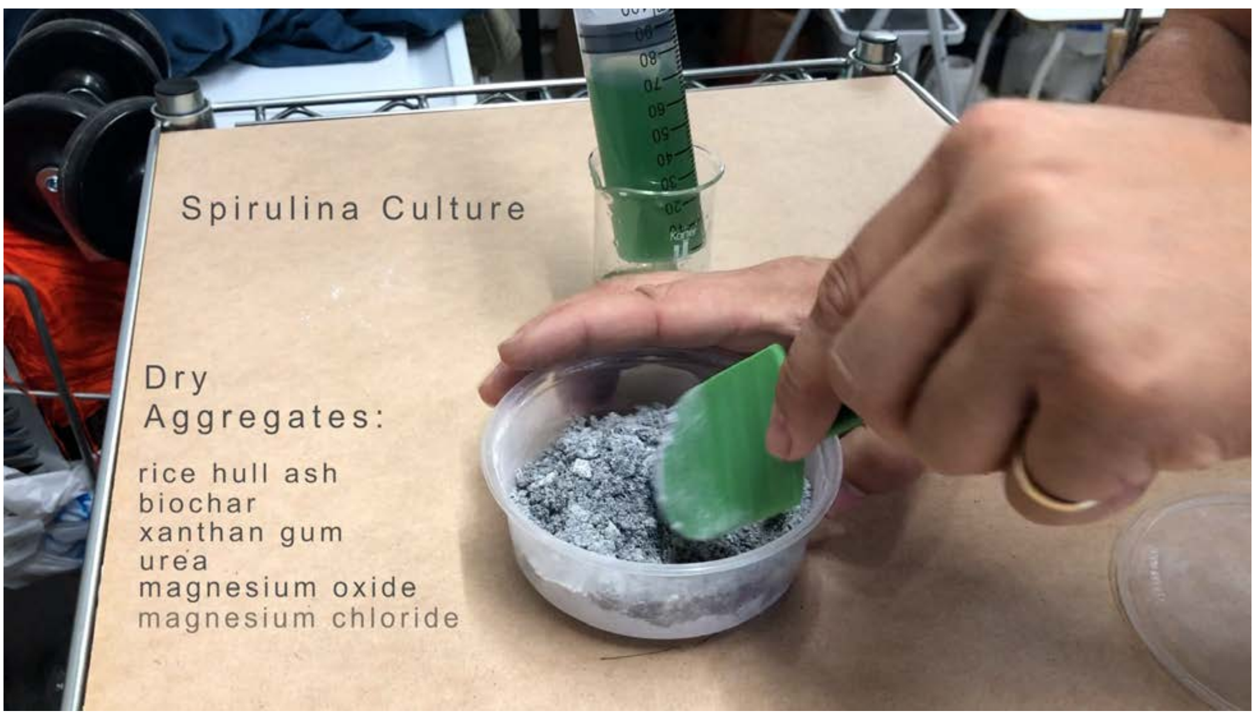
As mentioned on pg 29, the Carpet America Recovery Effort (CARE) incentivizes carpet waste landfill diversion and is developing a market for Post Consumer Carpet Calcium Carbonate (PC4). CARE estimates that 5 billion pounds of carpet was sent to U.S. landfills in 2017. While sourcing biochar from UC Davis biochar researchers, I was advised to also reach out to PC4 researchers, who like the biochar researchers were exploring the materials’ efficacy as a soil amendment. As PC4 contains over 70% calcium carbonate powder, it can serve as an alternative to conventionally mined calcium carbonate powder which is used as a conventional soil amendment to manage soil pH. In conventional concrete, calcium carbonate powder is used as a common additive. Incidentally the same PC4 researchers who were studying its application as a soil amendment were also studying its application as a cement and concrete additive. They were kind enough to provide me with a 1 gallon container of PC4 to use for BCC research with the theory being that PC4 could serve as the calcium source necessary to facilitate MICP.

Biochar

Biochar is the product of pyrolyzing biomass, typically agricultural waste products. I was unable to obtain specific information about the biomass source or the specific pyrolysis process for the biochar I was supplied by UC Davis biochar researchers. In general, biochar is regarded as a means of sequestering carbon by pyrolyzing biomass into stable carbon char, preventing it from naturally decomposing which emits more CO_2 and methane than does pyrolysis. Moreover, the remaining char has a high surface area to volume ratio, making it extremely porous. As a soil amendment, this porosity enhances soils' capacity to retain moisture and foster microbial life. As a constituent in BCC's, the theory was that its capacity for retaining moisture and fostering microbial activity would further support cementation processes like MICP in addition to serving as a carbon source.

Rice hulls

Not to be confused with rice straw, rice hulls are the shells that encapsulate grains of rice. Rice hulls have a high silica content, making them unsuitable to be fed to livestock and tilling them into soil can negatively impact soil quality. Globally, around 120 million tons of rice hulls are produced each year. When Rice Husk is burnt in controlled temperatures, Rice Hull Ash (RHA) is formed. RHA contains 60-90% silica, and The annual worldwide output of rice husk derived silica is more than 3.2 million tons (Patel 2017). For the project, three forms of rice hulls were used in BCCs. First, whole rice hulls marketed as livestock bedding were purchased from a local feed store. Second, some of the whole rice hulls were ground in a coffee grinder. Third, the UC Davis Green Engineered Materials & Systems (GEMS) Lab was able to provide industrial grade RHA which they had sourced from a biomass energy producer where RHA, like biochar, is a co-product of energy production. Of the three forms, RHA may have been the most significant and effective in both casting and extruding BCCs. It is incredibly lightweight, consisting of very thin linear particles that mix very well with most all other constituents and improve their overall workability and flowability.



Film still from [The Making of Aperiodic Table]

Urea & Chicken Manure

As mentioned on pg 27, urea is the predominant substrate source in MICP research. Urea is also used as a binder in other composite products like wood particle board, fiber board and oriented strand board. In addition to trialing with synthetic, power-based urea, chicken manure was also used as a biogenic alternative, as chicken manure has naturally high urea content. Moreover, chicken manure also fosters intense microbial activity which could aid in the cementation process. The results from multiple castings using chicken manure suggested it might also replace the need for magnesium chloride. Like Xanthan Gum, chicken manure would thicken wet BCC mixtures but also include thin wood chip like pieces which would prevent it from being used in BCC mixtures for direct extrusion via 3D printing.

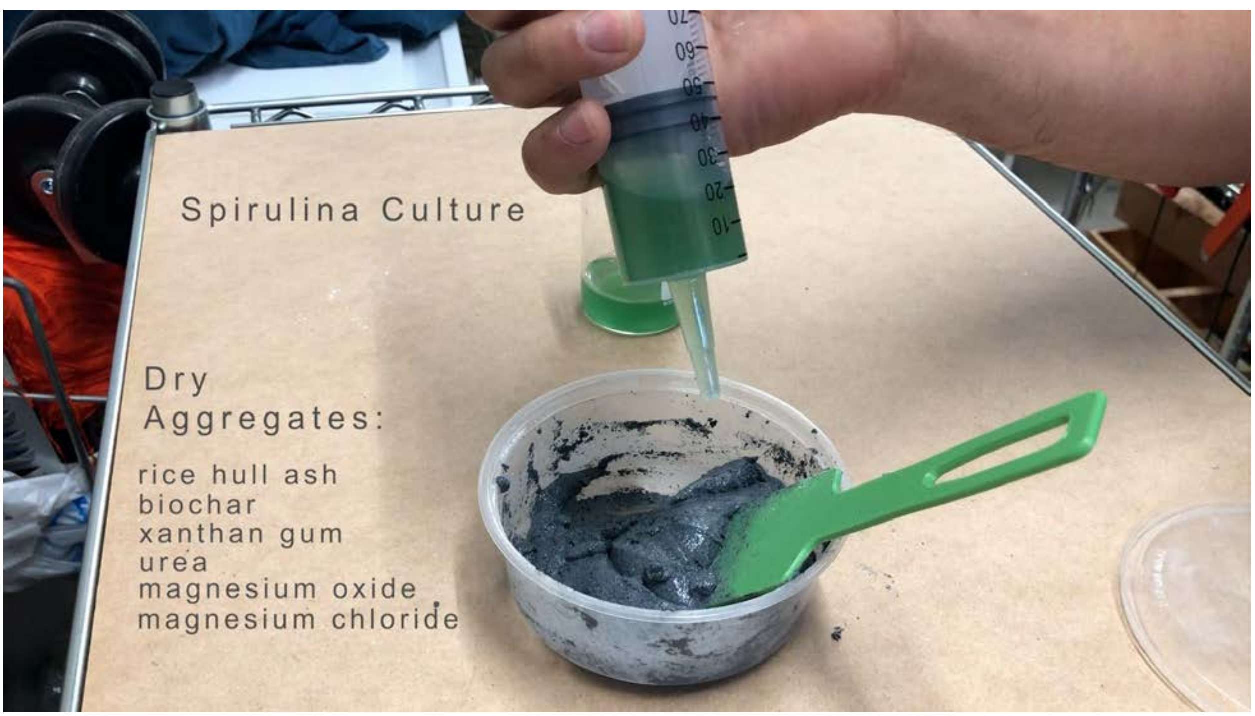
Magnesium Oxide & Magnesium Chloride

Within the academic literature of concrete research, is a 2016 literature review on magnesia-based cements by Walling & Provis that describes the cement industry as a global monoculture of Portland cement that punctuates a much longer history of construction materials having much more localized variation in which magnesia-based cements once had more significant roles and research & development interests. Walling & Provis' advocacy for magnesia-based cements is in part driven by "the lower temperatures required for the production of MgO compared to the conversion of $CaCO_3$ to Portland cement and the energy savings associated with this reduced temperature..."

One of the magnesia-based cements they profile as an energy saving alternative to Portland cement is Magnesium Oxychloride Cements (MOC) aka Sorel cement. First described in patents filed by the inventor Sorel in 1866, MgO and $MgCl_2$ are combined to form a gel in which basic magnesium chloride salts precipitate. MOCs have unique properties including a marble-like appearance, fire resistance, acoustic damping, ability to bind a variety of aggregates, and good compressive and tensile strength. It found applications as an ivory substitute for billiard balls, door handles, tiles, flooring and burial vaults.

Given than Magnesium Oxide powder is readily available as a ceramic glaze material, Magnesium Chloride crystals are readily available as consumer road salt, and that the MOC cementation process takes less than 24 hours according to the literature, it seems to be a good point of comparison to MICP-based cementations. MOC ended up being the only known means of successful cementation in the project. I was unable to confirm successful MICP to be removed from a silicone mold or 3D printed.

The ability to source magnesium oxide and magnesium chloride from saltwater, wastewater brine, and desalination brine has particular meaning today as we think about rising sea levels, climate change, wastewater management and water conservation and resilience. Sourcing or recovering materials from wastewater and other waste streams rather than conventional mining is another aspect of finding alternatives to conventional cement. It leads to the question of if not magnesium oxide, what other materials for cement could be recovered from these "wet" waste streams?



Film still from [The Making of Aperiodic Table]

Xanthan Gum

Xanthan Gum is most well known as a food additive. It is a powder that acts as a thickening agent and a stabilizer for preventing separation between ingredients. One of its most common applications is in commercial salad dressings to prevent the separation of oil and vinegar in addition to thickening the overall solution. It was invented by USDA chemist Dr. Allene Rosalind Jeanes in 1959 by working with the bacteria Xanthomonas campestris to ferment simple sugars in order to produce the powder. It would later find industrial applications, including the concrete industry where it is used to enhance viscosity and reduce risk of bleeding and segregation in wet mixes as they are curing. During this project, xanthan gum was instrumental in making the transition from casting wet BCC mixtures in molds to smoothly extruding them via 3D printer and ensuring the extrusions would hold their own form without the aid of formwork.

2) Casting Composites

Phase 1 Prototype A | Phase 1 Prototype B | Phase 1 Prototype C

Initial Prototypes using 2"x2" nursery pots

Like the majority of the research literature, most experiments for biogenic cement composites and MICP involve casting composites with the use of molds. Meanwhile, whether precast, or poured in place, nearly all practical applications of concrete require molds and formwork. Initial prototypes were cast in generic 2" x 2" nursery pots, then several one-part silicone molds were fabricated to test a module with a more complex form for reasons that will be discussed in the next section focusing on the final sculpture. To fabricate the silicone molds, master molds were 3D printed using an Ender 3 3D printer and generic PLA filament. A 2-part translucent non-toxic silicone rubber liquid for mold making was then poured into the master molds. Once the silicone cured, the molds were removed from the 3D printed master molds and ready to cast BCCs. The pliability of silicone molds was necessary to help minimize any breakage that might occur to a casting while removing it from a mold. Yet the weight of the wet BCC mixtures caused the pliable mold walls to bow, requiring a rigid outer mold shell to be 3D printed and additional laser cut sheets of MDF to prevent bowing in a filled mold and ensure that the silicone mold could be successfully removed after curing. Out of 36 castings, 23 were removed successfully without any cracking.

Label	**A07**	**A06**	**A01**	**B18**	**B17**	**B02**	**A02**
Date	**2021.05.11**	**2021.05.11**	**2021.05.11**	**2021.05.11**	**2021.05.11**	**2021.05.11**	**2021.05.09**
Type	**A**	**A2**	**A3**	**B**	**B2**	**B3**	**A**
Constituents (wt in grams)							
Sand							
Carpet Powder	-	-	-	-	-	-	-
Water Crystal	-	-	-	-	-	-	-
Chicken Manure	30	20	30	25	30	46	-
MgO	120	100	120	100	100	100	120
MgCl2	10	20	20	17	20	20	40
Biochar		-	18	-	20	11	-
Spirulina Culture	170	130	160	160	185	130	140
Rice Hull Ash	15	15	15	-	18	15	-
Diatomaceous Earth	20	20	23	40	35	25	50
Rice Hulls Whole	8	10	-	6	-	-	15
Rice Hulls Grounded	-	-	-	-	-	-	-
Oyster Shell Grounded	-	-	-	-	-	-	-
Gypsum Board Grounded	-	-	-	-	-	-	-
Xantham Gum	-	-	-	-	-	-	-
Pig Iron Slag	-	-	-	-	-	-	-
Sodium Alginate	-	-	-	-	-	-	-
CaCl	-	-	-	-	-	-	-
Urea	-	-	-	-	-	-	10
Spirulina Powder	3	-	-	-	-	-	-
Water	-	-	-	-	-	20	-
Dry Sum	132	155	141	110	103	104	170
Comments	cracked while pulling out of mold, light & paper-like					corner cracked o	DIAGONAL CRA
Cracking	**y**					**y**	**y**

Excerpt from BCC Formula & Testing Matrix

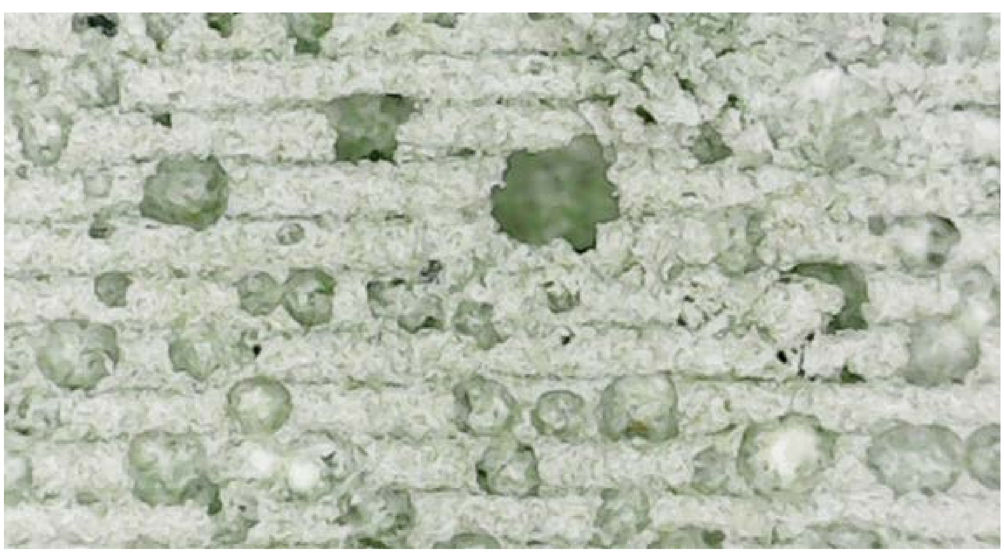
In addition to the one-part silicone molds, two-part plaster molds were also attempted. The technical rationale being that the high pH of plaster would help foster alkaliphilic microbial activity both in the Spirulina culture and among any other native microbes in the various BCC mixture constituents. The cultural rationale being that plaster molds are widely used in ceramic slip casting practices which in turn would lead to a broader user/beta testing group for BCC research and development. However, several early attempts of pouring wet BCC mixtures into two-part plaster molds resulted in the BCC mixture sticking to the plaster molds and cracking both the BCC casting and plaster mold during removal, limiting the scope of the project to silicone molds. Developing a BCC specific for slip casting and a BCC as an alternative to plaster molds would be great lines of inquiry to revisit given slipcasting's reliance on limestone calcination for plaster and energy heavy kiln firing.

Film stills from [The Making of Aperiodic Table](), Module A removal from silicone mold

Throughout the research, I was fortunate to take UC Davis ceramics courses which informed inquiries and provided tremendous guidance on setting up a home studio practice during COVID restrictions. The community, culture, skillsets and history of ceramics is inherently inquisitive, research-driven, lab-like and accustomed to the regular transformation of materials. At the same time, concepts like thingpower, Gongshi and Hòn Non Bộ resonate well in the community. Ceramicists and artists working in ceramics are constantly experimenting and trialing with many of the same materials and methods required of BCC development and with similar applications in mind. Trialing material apportionments in cementations is akin to trialing material apportionments for clay bodies, glazing and firing. Moving forward, ceramicists, like material scientists, would be crucial and creative partners in researching and developing BCCs, effectively communicating their importance to broader audiences as early adopters and practitioners.

Moreover, the ceramics community stands to mutually benefit economically, ecologically, socially and greatly from less reliance on kilns, mineral extraction, limestone calcination and other means of decarbonization in addition to BCC adoption.

Film stills from [The Making of Aperiodic Table](), Module B removal from silicone mold



Microscopic image of surface of a BBC casting

3) 3D Printing Composites

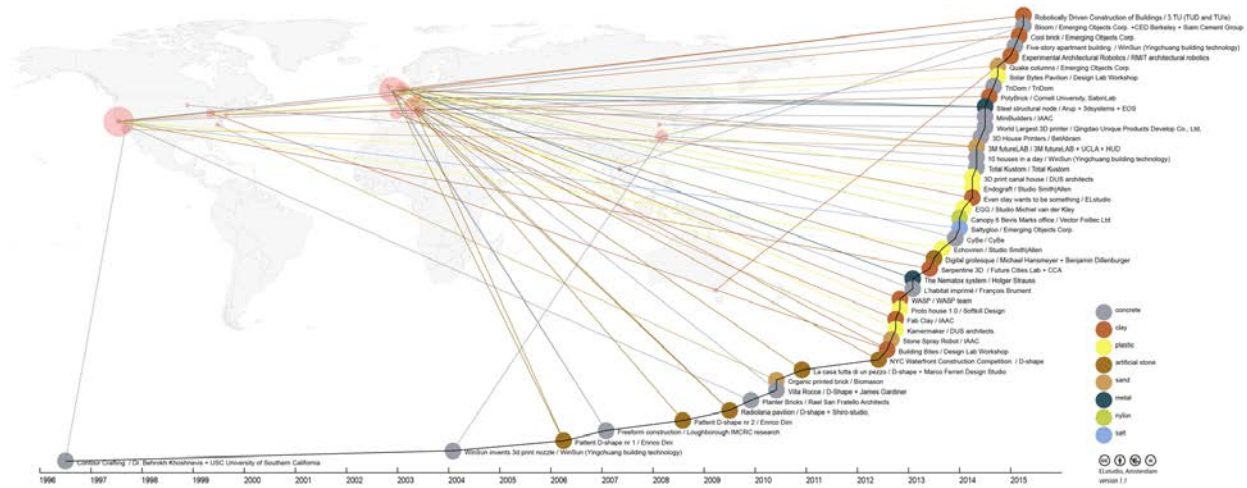
> *"In the US, formwork costs up to 60% of the total cost of construction, and often is discarded after use. However, in the case of 3D-printed concrete, there is no formwork, which means that potential advantages include lower labor costs, increased complexity without specialized labor, greater accuracy, less waste, and less use of water. All add up to make 3D-printed concrete potentially more sustainable and accessible to a wide array of concrete gourmands." (Rael & San Fratello, 2018)*

Adopting at home 3D printing with PLA filament for the initial prototyping of models to be cast led to 3D printing the master molds for the silicone molds which then led to 3D printing countless other tools and parts that were needed throughout the project, including a transparent chassis for one of the Spirulina bioreactors. Meanwhile, 3D printing was getting more and more prevalent throughout design literature as well conventional cement, concrete and ceramics literature. There were also several noteworthy full scale buildings that were 3D printed during the project period, including Rael & San Fratello's *Casa Covida*. These conditions ultimately lead to a new fundamental research question: *If biogenic cement composites (BCCs) are to be widely adopted for long term mitigation of environmental degradation and reconciliation ecology, is it more important to consider and collaborate with the outlying and rapidly growing 3D printing community or the larger, more centralized, mold/formwork community for conventional ceramics and concrete?*

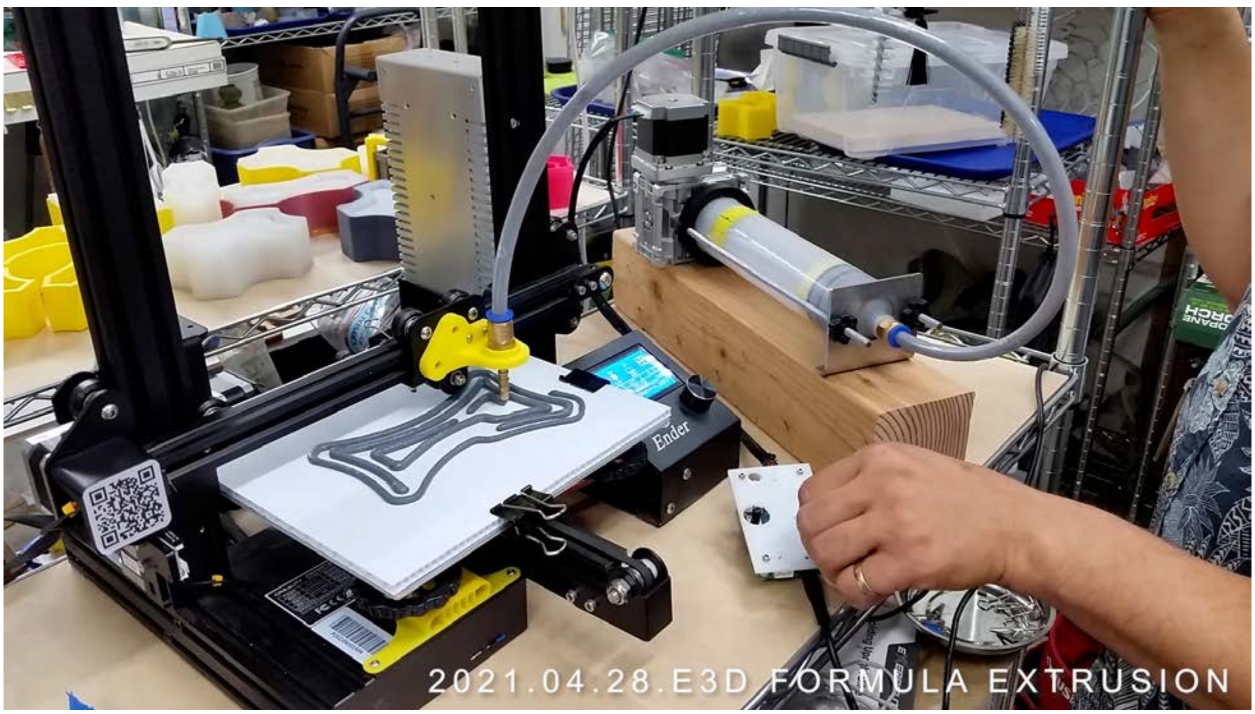
I successfully applied for a special projects stipend from my department to explore this question and developed a parallel line of inquiry into producing 3D printed versions of the same BCC modules which would require different formulas in order to maintain their composure without the aid of a mold or formwork. I was using an Ender 3 desktop FDM printer for my initial 3D printing with PLA filament and was able to find a 500 mL paste extrusion kit from Cerambot which could convert FDM printers to extrude pastes rather than filaments. I was then able to find several online user groups dedicated to 3D ceramic/clay printing which, like the UC Davis research community, was extremely generous in sharing knowledge. So with their help I was able to configure the hardware and software to then trial different constituent apportionments to get BBC mixtures that were compatible with the modified 3D printer. Experimenting with layer depth, extrusion feed and speed rates and toolpaths were coupled with BCC mixture parameters in order to get working prints. Initial experiments were simply hand guided and single layer but slowly iterated upon to ultimately reach the same height as the mold casted modules.

The project title "Recasting Resilience" initially referred to how the typical roles of these materials and the larger roles of waste and industries might all be 'recast'. However, looking back at the development of the project, the process of casting itself also had to be reconsidered in light of the efficacy and proliferation of 3D printing. Moving forward, I am excited to explore how 3D printing technologies can also be 'recast' to automate and integrate the apportionment and mixing of aggregates and constituents into extrudable pastes.

Film still from The Making of Aperiodic Table

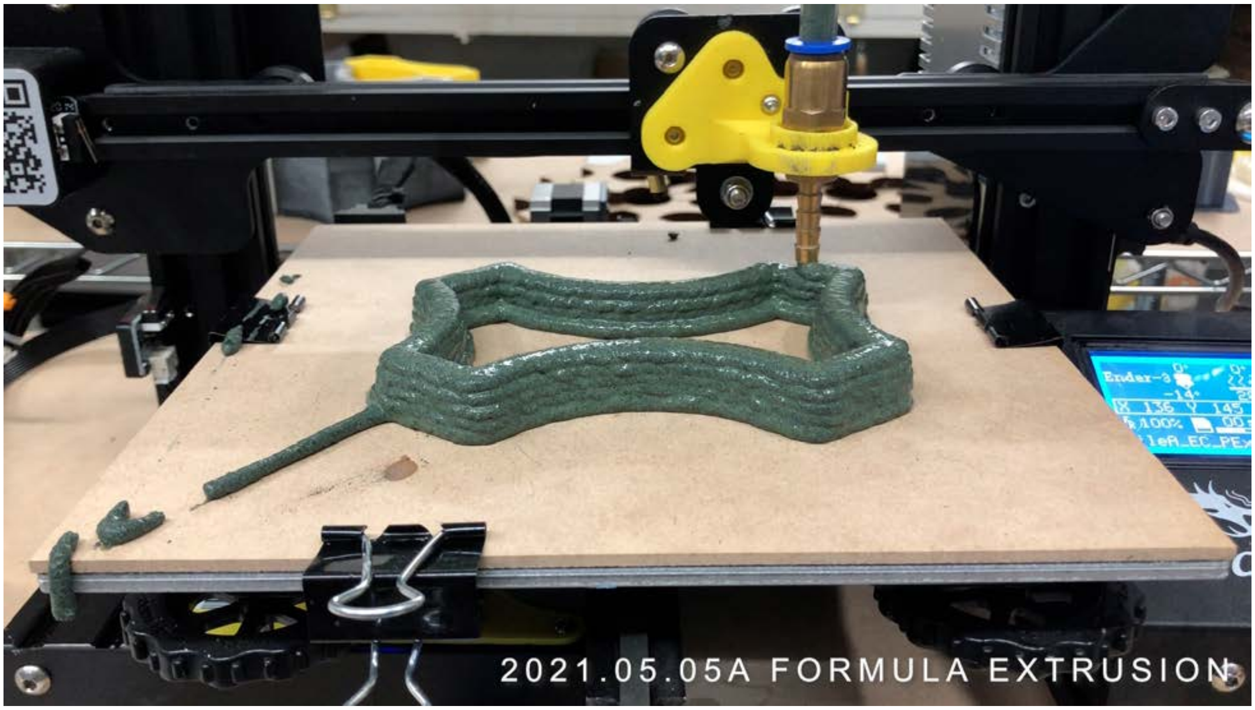


Mapping 20 year of 3D Printing in Architecture, Erno Langenbertt, [ELstudio]



Film still from [The Making of Aperiodic Table]

Film still from [The Making of Aperiodic Table]



Film still from [The Making of Aperiodic Table]

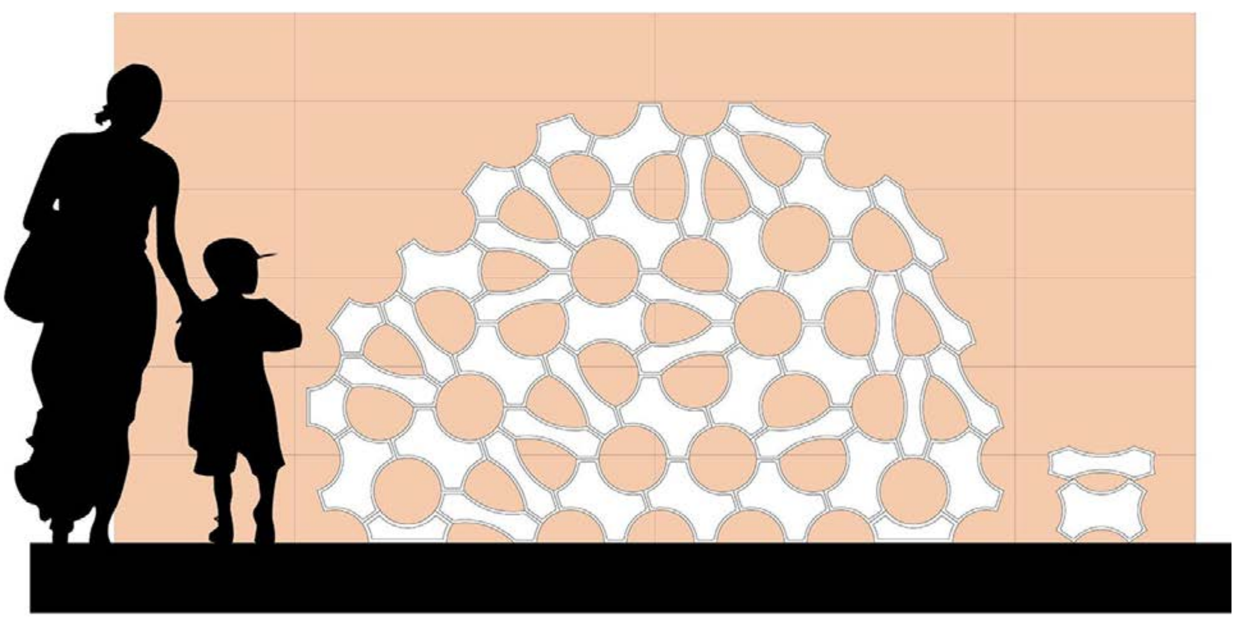
APERIODIC TABLE: A BI-MODULAR RESEARCH SCULPTURE

The final design outcomes for studio-based material research projects take on many forms. Pavilions, furniture, lighting fixtures, apparel, diapers and other consumer facing objects with clear user affordances provide a common strategy for engaging broad audiences with a new biomaterial that they might be unaccustomed to. Prescribing applications for BBCs at the time didn't seem appropriate for the project, the severe global issues it addresses or the many roles and paradigms it hopes to recast. Instead, ambiguity and abstraction were adopted to invite speculation amongst the audience on how BBCs could be implemented in ways most relevant to them. It was also vital to emphasize the work was incomplete and ongoing and to invite research relationships and collaborations rather than market adoption. Ambiguity and abstraction led to a modular sculpture that could be reconfigured and amended as new and better performing BBCs would be developed over time.

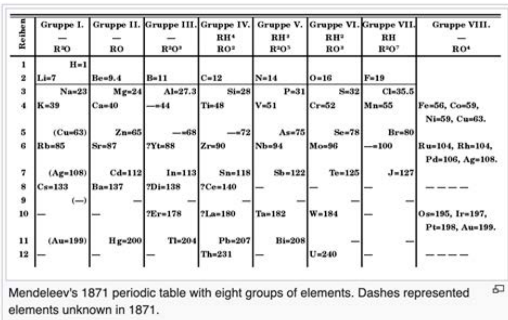
Visiting different labs and meeting researchers throughout the project corroborated this concept and further motivated me to collaborate with scientists in mutual ways. In visiting different labs, it was easy to become concerned with how research artifacts were kept. Glass vitrines would house artifacts in an unflattering light. Beautiful Gongshi-like pieces of concrete and BCCs were kept in dark closets, not being appreciated by anyone, invisible, not furthering new research or collaboration. My simple value proposition was to bring their work out of closets and into galleries. Beyond that, I was compelled to present BBCs standing on their own, without intermediate materials like the

Vitrine at Neuro Sciences Center, Tod Williams Billie Tsien Architecture, San Diego, 2021

glass vitrine or shelves. Modular castings and printings of different BCC formulas ought to 'aperiodically' aggregate together to form a whole, repeating what was happening within the BCCs at their microscopic level. The voids in and between modular castings would remain empty as spatial placeholders for the audiences' ideas and speculations of how BCCs could be used. New modules could be added as



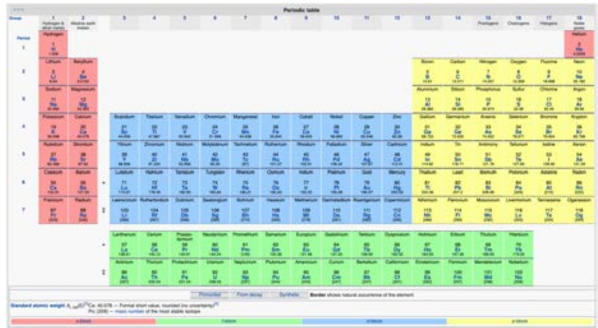
Initial rendering of Aperiodic Table, inspired by Gongshi and Prosolve370e research continued, continuing the Gonshi-like pattern and composition rather than go into a closet or vitrine as artifacts. In this way, they could take on the "neither made nor grown" basket weaving-like quality that Tim Ingold observed (pg 6). The title name 'Aperiodic Table' encapsulates this form, concept and pays respect to the Periodic Table of Elements which organizes elements, adds new ones as they are discovered and stands as the epitome of scientific collaboration and science communication.



Reihen	Gruppe I. — R^2O	Gruppe II. — RO	Gruppe III. — R^2O^3	Gruppe IV. RH^4 RO^2	Gruppe V. RH^3 R^2O^5	Gruppe VI. RH^2 RO^3	Gruppe VII. RH R^2O^7	Gruppe VIII. — RO^4
1	H=1							
2	Li=7	Be=9.4	B=11	C=12	N=14	O=16	F=19	
3	Na=23	Mg=24	Al=27.3	Si=28	P=31	S=32	Cl=35.5	
4	K=39	Ca=40	—=44	Ti=48	V=51	Cr=52	Mn=55	Fe=56, Co=59, Ni=59, Cu=63.
5	(Cu=63)	Zn=65	—=68	—=72	As=75	Se=78	Br=80	
6	Rb=85	Sr=87	?Yt=88	Zr=90	Nb=94	Mo=96	—=100	Ru=104, Rh=104, Pd=106, Ag=108.
7	(Ag=108)	Cd=112	In=113	Sn=118	Sb=122	Te=125	J=127	
8	Cs=133	Ba=137	?Di=138	?Ce=140	—	—	—	— — — —
9	(—)	—	—	—	—	—	—	
10	—	—	?Er=178	?La=180	Ta=182	W=184	—	Os=195, Ir=197, Pt=198, Au=199.
11	(Au=199)	Hg=200	Tl=204	Pb=207	Bi=208	—	—	
12	—	—	—	Th=231	—	U=240	—	— — — —

Mendeleev's 1871 periodic table with eight groups of elements. Dashes represented elements unknown in 1871.

Periodic Table, Dmitri Ivanovich Mendeleev, 1871



Periodic Table, Wikipedia, 2021

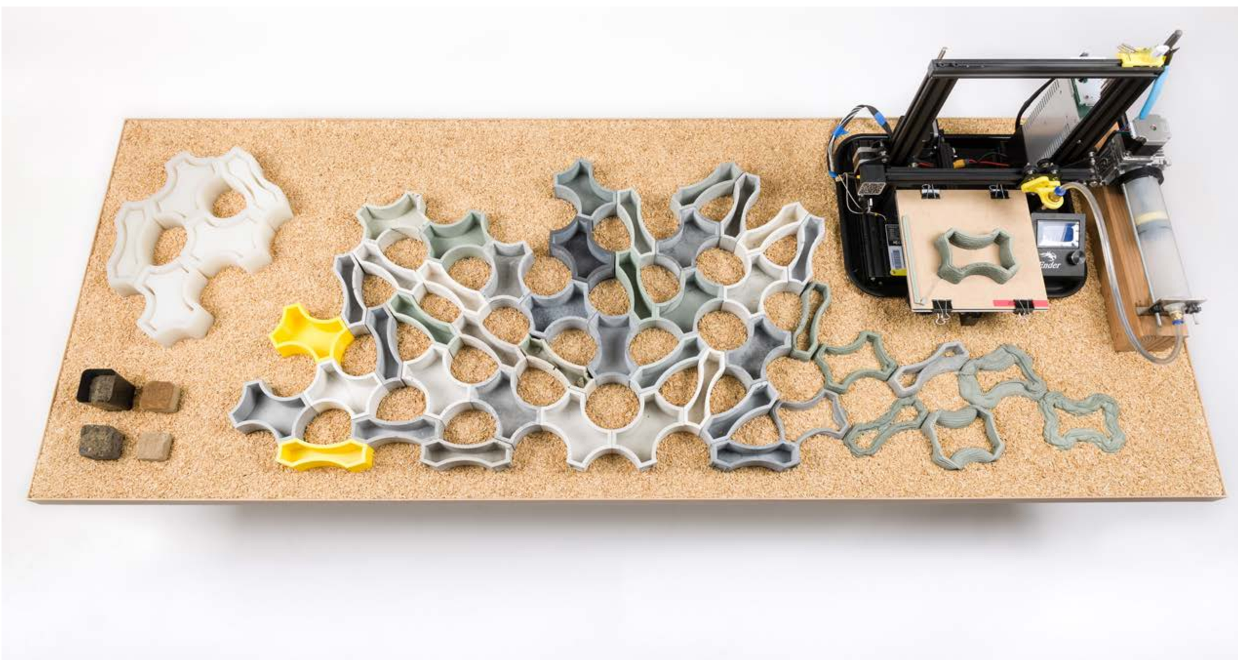
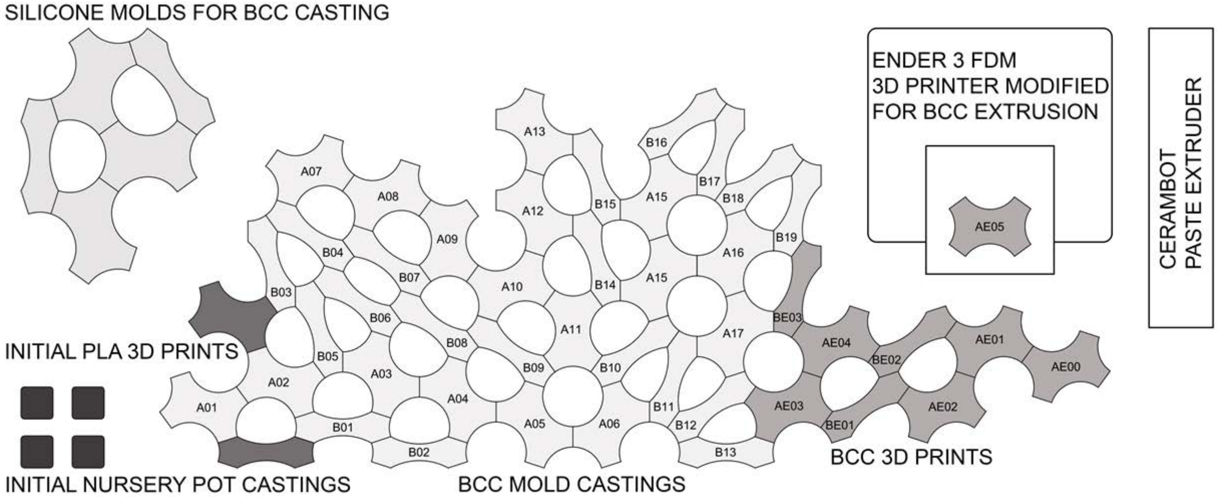


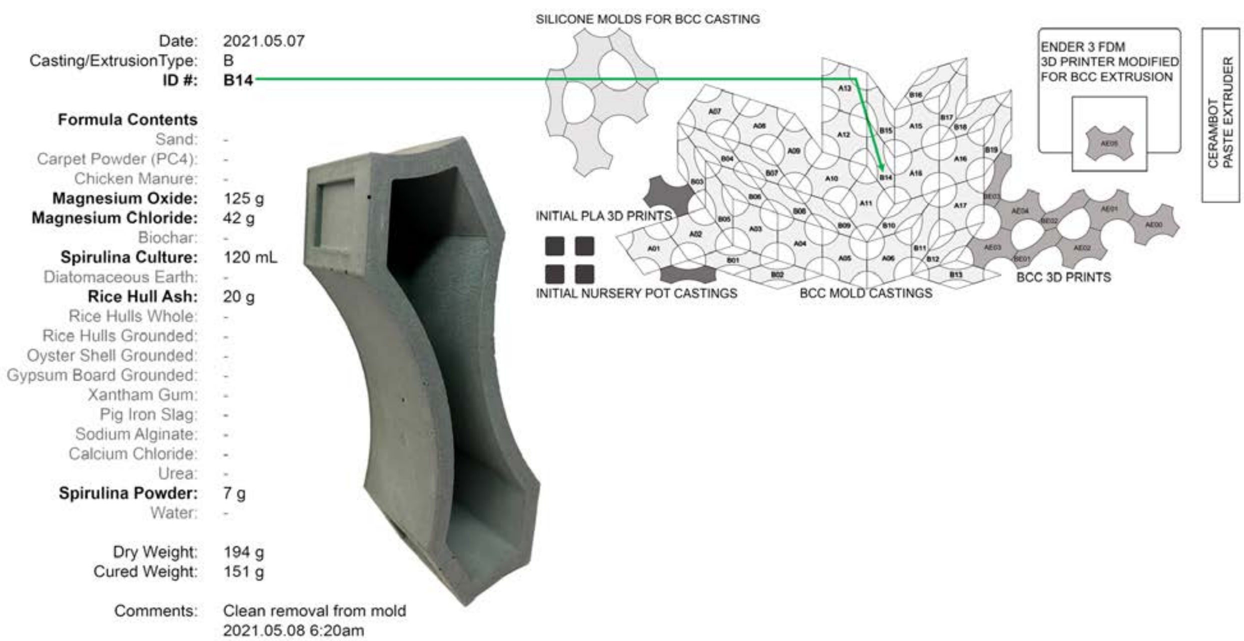
Photo of Aperiodic Table, Manetti Shrem Museum MFA Virtual Exhibition, 2021



Explanatory diagram of Aperiodic Table, Manetti Shrem Museum MFA Virtual Exhibition, 2021

In its first iteration as a virtual exhibit for the 2021 Manetti Shrem Museum MFA Virtual Exhibition, the initial castings and extrusions are arranged horizontally on top of a layer of rice hulls from which many of them were formulated. The silicone molds and 3D printer are also incorporated into the tabletop display. While this is intended for broad audiences and to encourage audience speculations, it is also meant as a proof of concept and audition for future partners who might be interested in contributing to the 'Aperiodic Table' as a reconfigurable, growing, traveling exhibit.

In partnering with other material researchers through the future project, it would be great to pursue further material testing and analysis with the necessary equipment to keep developing the efficacy and performance of BCCs now that this new artistic framework for science communication and collaboration is established. Likewise, digital fabrication, computational designers and machine learning specialists would be tremendous partners in further optimizing formula apportionments and fabrication parameters to refine production processes, equipment and other hardware. In partnering with other artists, designers, reconciliation ecologists, microbiologists and others, I am excited to exchange and develop best practices that continue to blur all disciplines, built and unbuilt, art and science, anthropogenic and non-anthropogenic. Most importantly, I am excited to see and be part of future speculations, applications and partnerships that go beyond gallery exhibitions to foster a more circular culture capable of recasting and reconciling our anthropogenic mass and habitat.



Explanatory diagram of Aperiodic Table, Manetti Shrem Museum MFA Virtual Exhibition, 2021

Film still from [The Making of Aperiodic Table]

Film still from [The Making of Aperiodic Table]

Film still from [The Making of Aperiodic Table]

Film still from [The Making of Aperiodic Table]

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