Geomorphic Concrete

Material and fabrication strategies for heterogeneous concrete morphology

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ABSTRACT

Given evidence of climate change and the global supply chain crisis, it is no longer viable to continuously exploit nature and expect the global industrial system to remain perpetually dependable. We have to prepare for a world that is not entirely controllable or measurable, which is an inevitable architectural condition of the future. This thesis introduces *geomorphic concrete*, an alternative design approach and construction methodology closely aligned with geological formation process by incorporating natural forces as collaborators in concrete fabrication.

Geomorphic concrete is an alternate paradigm of material-based design and construction methodology achieved by exploiting the variation in material properties respond to elemental forces. Nature shapes geological formations through a diverse array of materials and natural forces. For example, sedimentary rock's stratified planes have varied grain, strength, and other characteristics, resulting in unique shapes and patterns through natural processes such as weathering, erosion, and sedimentation. A series of experiments in this thesis demonstrates how to design and construct concrete structures by mimicking the natural geological formation process, instead of relying solely on modernistic geometry-driven design.

This methodology utilizes an injection-printing fabrication technique, inserting reinforcement and suspension materials in liquid concrete to produce cast objects with varying material properties that erode, break, reconfigure, and recover through engagement with natural agents. The thesis showcases three designs that exemplify geomorphic concrete: a material-based structure design by fabricating heterogeneous concrete; a concrete structure printed into granular formwork that erodes due to gravity; and a concrete object that evolves over time by dissolving the injected suspension material.

This thesis contributes to acknowledging geological formation as a ecological process and developing an architectural fabrication concept that embraces elemental forces and material changes as agents in the building process.

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1 Prologue

A slow approach for urgent issues

This thesis chronicles my journey to address a question that has intrigued me since my earliest days in the architecture industry. Having worked in five different firms across North America, North Europe, and East Asia, I have observed that although the details of design approaches may differ, the process remains equally static and linear. Architects design a form, engineers analyze structures and prices, and construction methods are negotiated based on budget and time at the final stage of the design process.

This rigid design process in practice and blind trust in standard materials are not viable in architectural conditions that are not entirely controllable and measurable. While writing this thesis, I continued to work on construction documents for a house in Hanoi, Vietnam. I was working on sets of drawings for precise construction 8,000 miles away from me during the night. All this struggle was a result of fitting local material conditions and technical availability into geometry that I designed months ago in CAD. What if designers could design a material and formation process instead of the finalized shape of the building?

In the future, more architectural conditions will not be able to rely on standard products and construction procedures that guarantee precision in construction. As I have introduced from my experience, many parts of the world have been facing this issue. I envision a paradigm shift in how we make architecture and what we expect from it in a world that is not entirely controllable or measurable. The series of experiments I introduce in this thesis trigger the imagination of alternative ways of making architecture: being inaccurate to be accurate, inefficient to be efficient, and slow to address urgent problems.

2 Introduction

Modern concrete construction relies heavily on standardized materials, design, and fabrication methods to achieve high precision in construction. This approach results in excessive consumption of labor and materials to achieve the ideal geometry as designed in CAD. What can be achieved if architectural design allows more tolerance in construction and the involvement of various agents in the formation process?

My thesis introduces the concept of *geomorphic concrete*, and explores new paradigms of material-based design and fabrication in which the architect enters into an uneasy design collaboration with forces of nature. Geomorphic concrete fabrication engages additive and subtractive morphological processes that are found in nature such as erosion, sedimentation, deposition and aggregation. The material composition of geomorphic concrete is designed to take on a given low resolution form through the design of and encounter with fabrication forces that are neither entirely predictable or calculable, nor completely random. Geomorphic concrete argues that low resolution design and fuzzy fabrication which celebrates the planned loss of presumed architectural control may be advantageous for future practices. Geomorphic concrete holds the potential to move the discipline of architecture away from modernist notions of static, monolithic materiality of concrete, and linear methods of design agency and construction control. It is necessary to question these assumptions given the climate crisis and the construction industry's current usage of wasteful, high energy and labor-intensive fabrication processes.

In light of mounting evidence of resource depletion and the ongoing global supply chain crisis, it is no longer acceptable to rely on the belief that architecture and construction practice can continuously exploit nature, and assume that the modern industrial system, which is based on international specialization and trade, will always be dependable. The future will involve conditions for architecture and design agencies that are not entirely controllable or measurable (Hill, 2001). It is not viable for architects to maintain and continue with conventional ideal geometry-driven design methodologies, which requires excessive material and energetic consumption and labor for tolerances that are unachievable.

To address issues of modern concrete design and construction, it is important to understand how the architectural industry arrived at its current standardized material notion and fabrication method. There are various accounts regarding the origin of concrete, but according to Peter Collins, the first historian to research architectural concrete, artisans developed early concrete in the late eighteenth century and early nineteenth century France as a means of improving traditional pisé (rammed earth) construction (Collins et al., 2004). Because concrete was originated from traditional mud construction and its early development relied on local trial-and-error experiments, it was not initially viewed as an advanced or scientific material. It was not until the early nineteenth century that French engineer Louis-Joseph Vicat published scientific research on the chemistry of cement, and the cement industry made efforts to promote concrete as a progressive material. Only then did concrete begin to gain a reputation as a product of scientific technology (Forty, 2013). In the twentieth century, concrete was widely regarded as a symbol of modernity by closely associated with the representation of modern architecture (Programmes and Manifestoes on 20th-Century Architecture, 1970). Despite its progressive image, concrete still retains several rudimentary features. For instance, the construction of concrete structures relies heavily on skilled craftsmanship, from assembling reinforcing elements to fabricating formwork. From this history, it is

Figure 2.1. Flooded Modernism: Artist Asmund Havsteen-Mikkelsen sunk a scale model of Le Corbusier's Villa Savoye for Floating Art Festival on the Vejle Fjord. The powerful image of a box-shaped white concrete modernism symbol sinking in the water from melted glacier water questioned me about the new value and approach of changing society and climate. Danmark, Asmund Havsteen-Mikkelsen - Reprinted from vejlemuseerne.dk, 2018.

evident that there is a significant disparity between the concept of concrete and the actual process of its construction.

Our understanding of concrete is not based solely on a natural law of the material but is also socially constructed and restricted (Bardt, 2019). Essentially, our conception of concrete is influenced by human desires and preferences. Following the Industrial Revolution, a standardized understanding of construction materials was developed to facilitate mass production and precise construction (Picon, 2005). However, as Timothy Graham Cooke argues, concrete is inherently heterogeneous, and modern industry has attempted to make it more uniform (Cooke, 2012). Treated as homogeneous, isotropic, and static, concrete served the form-driven design methodology of modernism, which separated the shape, structure, and material of buildings in a linear process of modeling, analysis, and construction (Oxman, 2010). This rigidity in the design process and the multiple steps of construction require excessive consumption of material and labor (Havsteen-Mikkelsen, 2018). For example, architects often design complex geometries without considering the economic and ecological cost of their construction, leading to the consumption of more resources to fabricate delicate formwork. In fact, the formwork alone accounts for more than half the resources necessary for concrete structures (Antony et al., 2014). Therefore, the continued use of modernist design methods and concrete fabrication processes that prioritize perfect geometry is not sustainable due to the scarcity of skilled labor and the environmental impact of wasteful fabrication processes (Adaloudis & Bonnin Roca, 2021).

In contrast, the geological formation process is a ecological system of materials and forces that operates from the material composition of individual rocks to the entire shape of a landscape. The heterogeneous structure of sedimentary rocks, with varying grain sizes, strengths, and other characteristics, defines the shape of the landscape. Conversely, the shape of the landscape influences how the materials erode, are deposited, and metamorphose, resulting in sedimentary rocks (Hutton, 1788). Also, unlike energy and labor-intensive building construction processes, nature shapes geological formation through a diverse array of materials that respond to natural forces. For example, sedimentary rock's multiple stratified planes with various material properties resulting in unique shapes and patterns through natural processes such as weathering, erosion, sedimentation, and petrification.

Learning from the logic of geomorphology, this thesis conceives concrete as an adaptable material that can accommodate various material properties, and re-envisions natural material transformations as an advantage, moving away from traditional static and monolithic material concepts. Concrete can be designed to be a heterogeneous and anisotropic material that ultimately has the potential to evolve with natural forces such as erosion and dissolution. Unlike modern design and construction process that heavily relies on standard products, this method reveals a unique shape that represents a specific material condition and event that was not predictable or calculable, yet not completely random. Additionally, this new materiality and geological way of construction require less formwork and labor. A series of

Figure 2.2. Geological formation: The heterogeneous structure of sedimentary rock resulted in various levels of erosion in different parts of the rock. White Desert National Park, Egypt, Lau Svensson - Reprinted from en.wikipedia.org/wiki/White_Desert_National_Park, 2013.

Figure 2.3. Eroding formwork: Concrete was cast inside the 3D-printed gypsum formwork. Gypsum formwork dissolved into water and eroded with time. The gypsum formwork left the mark of a fluid form of 3D-printed gypsum.

experiments in this thesis demonstrates how to design and construct concrete structures by mimicking the natural geological formation process, instead of relying solely on geometry-driven design.

Geomorphic concrete utilizes injection-printing technology, inserting reinforcement and suspension materials in liquid concrete to produce cast objects with varying material properties that erode, break, reconfigure, and recover through engagement with natural agents. The thesis showcases three designs that exemplify geomorphic concrete: a high-performance heterogeneous concrete structure with injected reinforcement materials; a concrete structure printed into granular formwork that erodes due to gravity; and a concrete object that evolves over time by dissolving the injected suspension material.

This thesis begins by examining the issues with modern design approaches and construction methods for concrete, tracing its complex history and social conception in the chapter Dual History of Concrete. The following chapter, Material Complexity and Variability, is a proposal for rethinking the material properties of concrete, that argues for changing the common concept of concrete from a homogeneous and static material to a heterogeneous and active one that leads to improvements in concrete construction. The final chapter of the Background, Geomorphic Design, introduces geomorphic concrete, a possible solution to transforming the paradigm of concrete construction from a wasteful and labor-intensive process to a sustainable and efficient fabrication method that integrates natural forces and phenomena into the building process, following geomorphological examples. The Add-Tractive fabrication chapter reviews the technologies and ideas related to the fabrication methods that inspired and were utilized in this thesis. Subsequent chapters in this document delve into the detailed processes and methodologies of the geomorphic concrete fabrication method, including tool development and material design.The Design chapter presents three fabrication methods that draw inspiration from natural geological formation processes. These methods include embedding reinforcement materials within liquid concrete, similar to how igneous intrusions form; allowing for natural erosion to remove formwork by utilizing gravity; and dissolving suspension material to reveal concrete forms, resembling the formation of solution caves. The concluding chapter will summarize the contributions of the thesis and discuss potential future work for geomorphic concrete, which emphasizes the use of materiality and natural forces rather than precise dimensions and mechanical power.

3 Background

3.1 Dual History of Concrete

Concrete has been consistently associated with modernity and advanced technology, as George Orwell categorized concrete construction as one of the principal symbols of modernization, along with science, progress, internationalism, aeroplanes, steel, and hygiene in his essay “Wells, Hitler and the World State (Orwell, 1975).” Adrian Forty similarly recognized the significance of concrete in mediating people’s experience of modernity, stating that “concrete tells us what it means to be modern (Forty, 2013).” However, despite its reputation as a key agent in shaping modernity, it is important to acknowledge that concrete has a complex history of how it has been socially perceived as modern and not-so-modern at the same time.

The reputation of concrete as a product of scientific technology is not naturally given, but achieved by the cement industry and modernist architects’ constant effort to associate concrete with advanced technology. For example, early pioneer in reinforcement concrete François Hennebique emphasized the modernity of concrete by its technical superiority, such as fire resistance and structural firmness over earthquakes, through integrating structural elements into one continuous system (Cohen & Moeller, 2006). Another attempt of connecting concrete to modernity is pairing concrete with principles and representations of modernism architecture such as simplicity and functionality. As a result of the socially constructed modernity of concrete, characteristics of concrete, such as ubiquity, predictability, and speed of construction, have changed the relationship between humans and nature by creating a living environment that is fundamentally different from the pre-industrial era. Cities and towns that were built by local craftsmen and resources were replaced by a monolithic style and material in a short period of time. However, this does not mean that concrete construction does not require skilled labor and resources as traditional construction methods.

In 1972, The Hall of Nations and Halls of Industries were constructed for the International Trade Fair in New Delhi, India. These structures were pyramid space-frames constructed of concrete tetrahedron units. Although those structures were intended to symbolize the nation’s industrial progress and modernization,

Figure 3.1.1. Halls of Nations and Industries under construction: Space structure was not built in pre-fabricated steel structure but in concrete because of the abundance of available laborers who could fabricate wood formwork and cast concrete on site. This story shows how concrete associates with two conflicting conceptions simultaneously: advanced technology and traditional craft. Raj, Mahendra, and Raj Rewal. Halls of Nations and Industries, Pragati Maidan, New Delhi, India - Reprinted from photograph by Madan Mahatta, architexturez.net/doc/az-cf-181543, 1972.

Figure 3.1.2. 3D printed Formwork: Digital Building Technologies in ETH developed hybrid of 3D printing and conventional casting fabrication method - Reprinted from Jipa & Dillenburger, 2022.

the decision to use concrete was actually based on the abundance of available laborers who could cast concrete on site, not because concrete represented as an advanced technology. This irony of the Hall of Nations and Halls of Industries highlights the complexity of concrete's social notion and history: the dual history of modern and non-modern.

While modern concrete is often associated with advanced technology, it is also considered primitive, unintelligent, and inefficient due to its monolithic material properties and wasteful fabrication process, which involves difficult formwork fabrication (Jipa et al., 2018). With conventional concrete construction, buildings are always built twice: first for the raising of formwork and then secondly the permanent structure is created within that formwork through the casting of concrete. The construction of formwork requires significant resources, and is highly dependent on skilled labor, accounting for over half of the resources used in concrete construction (Knaack et al., 2015). To combat the shortage of skilled labor and resource depletion, 3D Concrete Printing (3DCP) technology, which eliminates the need for formwork, have been introduced in recent years (Burger et al., 2022). However, the layered structure of 3DCP is weak under tension stress and is not suitable for large-scale structures (Yossef, 2015). 3D Printed Formwork (3DPF), a hybrid of 3DCP and conventional casting methods, has the potential to fabricate complex and unique optimized shape concrete structures faster and cheaper than traditional methods (Jipa & Dillenburger, 2022). One case study of high-rise residential tower in Brooklyn shows that 3DPF could make precast facade elements 60% faster with 25% of the costs of conventional timber formwork (Roschli et al., 2018).

These endeavors aim to enhance concrete as a more innovative and progressive material. Nevertheless, these methods have their constraints. Even though 3DCP and 3DPF can address numerous issues related to conventional concrete production, they give priority to geometric objectives while disregarding the intricacy and variability of concrete as a material. If concrete can be viewed as a substance that can be designed, the possibilities are vast.

3.2 Material Complexity and Variability

Children tend to paint water as blue and draw buildings with gable roofs, but these ideas are not the result of phenomenal insight. Instead, they are socially constructed (Bardt, 2019). As Theodor W. Adorno points out, forms and materials are more than simple natural phenomena but are shaped by history and cultural norms (Moravánszky, 2018, p. 16). He explained this by saying, “For the forms, even the materials, are by no means merely given by nature, as an unreflective artist might easily presume. History has accumulated in them, and spirit permeates them (Leach, 2005, p. 12).” Similar to many other notions, concepts of architectural materials are socially constructed through experiments, negotiations, and normalization processes (MacKenzie, 2001). After Enlightenment and Industrial Revolution, we developed static and monolithic notions of construction materials for mass production and reliable construction. Present notions of modern construction materials are heavily influenced by the nineteenth-century legacy of mechanics of continuous materials (Picon, 2005). For example, even though materials are not perfectly isotropic, standard reinforced concrete structures are designed in particular shapes and dimensions based on *Continuum Mechanics*, which ignores material property variation and sees concrete and steel as homogeneous mass (Fowler, 2005). Therefore, what we know about building materials is not a physical phenomenon of materials but what people desire from building materials for industrial demand. Timothy Graham Cooke supports this idea by stating that concrete is heterogeneous by nature, and that modern industry has attempted to make it uniform (Cooke, 2012).

The notion of materiality was more complex and comprehensive before the industrial revolution. There was no clear demarcation between the level of classification characteristic of structural material (Picon, 2005). People used to understand building materials in a broader organization include anisotropic organic materials, irregular shapes, and decaying materials. In many examples from the pre-industrial age

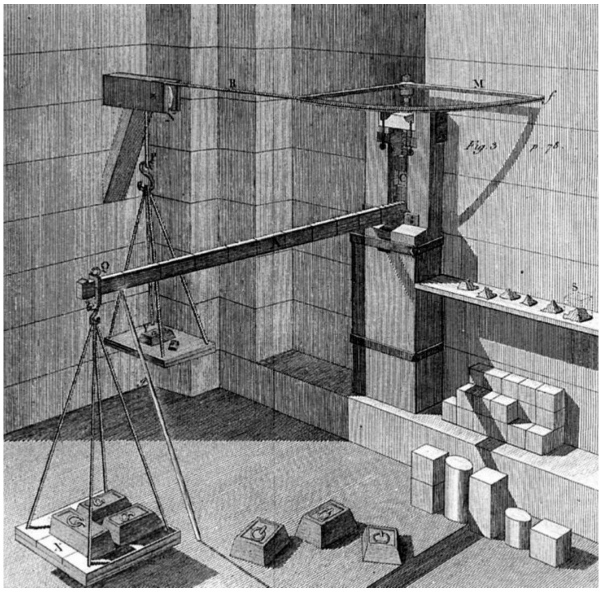


Figure 3.2.1. Machine to test the strength of materials: Connaissance des Materiaux published in Traité théorique et pratique de l’art de bâtir, Chez l’auteur - Reprinted from arpajournal.net, 1812.

Figure 3.2.2. Ox bones used as stone ties: The organic material was used in masonry construction in eighteenth-century Nantes - Reprinted from Picon, 2005 (Left).
Figure 3.2.3. Natural wood structure: Hwaeomsa temple in Korea used unprocessed tree as a column - Reprinted from Woo-Sung Choi, buddhaphoto.org, 2019 (Right).

buildings, we can observe a holistic conception of materials between organic and inorganic, structural and non-structural, permanent and temporary. For instance, ox bones (Figure 3.2.2.) were used for stone ties in eighteenth-century France (Picon, 2005), and unprocessed natural tree trunks were used for Hwaeomsa temple columns (Figure 3.2.3.) in Korea around the seventeenth century. This holistic material metabolism diminished in the modernism design method. Cyril Stanley Smith, metallurgist and historian who researched the development of the philosophy of matter in the West, explains how we lost conception of material complexity. He claims that craftsmen and blacksmiths, those who engaged in material production and fabrication, already had a conception of material complexity more than a thousand years ago. This notion was lost during industrialization because modern values such as precision and speed could not be achieved without simplifications (Smith, 1968).

Today, there are attempts to recapture this complexity and variability of materials in many disciplines, including material science, philosophy, and architecture. Material science investigates the complex behavior of matter beyond the obscure and simplified engineering of the monolithic behavior of materials (Leach et al., 2004). Philosophers Manuel DeLanda introduced an emerging concept of self-morphogenic matter (DeLanda, 2015). Also, an architectural historian Antoine Picon supports this idea by saying that people's material notion is returning to pre-industrial one with research on composite and smart materials (Picon, 2005, p. 15). In this context, designers now have two approaches to embracing material complexity and variability: material-driven design and generative design.

The material-driven design takes the material as the starting point of the design. In detail, it is a microscopic scale approach that uses material behavior or manipulates the material to perform better and more efficiently. For example, Cooke made a gradient aerated concrete that is similar to the bone structure, which is an anisotropic structure that has different strengths for different directions of forces (Cooke, 2012). generative design focuses on optimizing shape and arrangement based on unique load and use. Topology-optimized slab design by the Digital Building Technologies team in ETH is a good example (Jipa & Dillenburger, 2022). However, these approaches have their limits. The material-driven design uses prismatic geometry for its shape because its main focus is on material design behavior and performance. On the other hand, the generative design generates an optimized shape, but it uses the material in a traditional way. This thesis contributes to filling the gap between material-driven design and generative design in fabrication (Figure 3.2.4). One way to achieve this is to let the logic of the material generate the shape, as seen in geological formations, which is the oldest method of construction on Earth. This is called geomorphic design.

Geomorphic design is a methodology that combines material-driven and generative design approaches to create optimized shapes or objects that express the natural formation process rather than predefined geometry. Unlike traditional human craftsmanship, this methodology utilizes self-transforming materials or fabrication processes to allow the shape to emerge organically. The subsequent chapter will explain geomorphic design in greater detail and provide concrete examples.

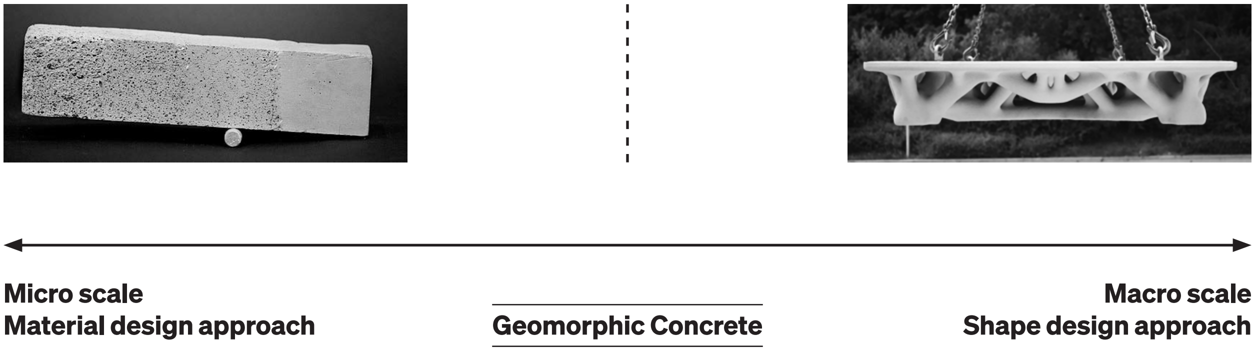


Figure 3.2.4. Mid-scale optimization: Geomorphic Concrete contributes to bridging the gap between microscopic scale material design and macro scale generative design approach. Left image in the diagram: Density gradient concrete, MIT, Steven Keating, Timothy Cooke and John Fernández, - Reprinted from news.mit.edu/2011/3d-printing-0914, 2011 (Left). Right Image in the diagram: Topology optimized slab, Digital Building Technologies, ETH Zürich, Andrei Jipa, Hyunchul Kwon, Mathias Bernhard and Philippe Steiner - Reprinted from dbt.arch.ethz.ch/project/topology-optimisation-concrete-slab, 2016 (Right).

3.3 Geomorphic Design

The geological formation is a system that operates at micro and macro scales, from the material composition of individual rocks to entire landscapes. Sedimentary rocks exhibit unique shapes and patterns, characterized by multiple stratified planes with varying grain sizes, strengths, and other properties. Natural processes such as weathering, erosion, sedimentation, and petrification shape these structures, and the resulting heterogeneous rock structures define the landscape's shape. Conversely, the formation of the landscape influences the mineral composition of rocks. The formation of a butte, an isolated hill with vertical sides like a standing column, illustrates how sedimented rock structures affect the larger scale of landscape shape. Stratified rock forms through a sedimentation process involving materials of different strengths and densities. Then, natural agents such as water, wind, and gravity carve out the weaker parts of the rock. Eventually, the erosion process reveals the shape of the butte.

James Hutton, a prominent figure in the development of modern geology, described a circular cycle of mineral formation, consolidation, and land formation. He noted that "There is a uniform system in nature of providing a power in the mineral regions, for consolidating the loose minerals deposited at the bottom of the sea, and for erecting those masses of mineralized substances into the place of land; we shall thus be led to admire the wisdom of nature, providing for the continuation of this living world, and employing those very means by which, in a more partial view of things, this beautiful future of an inhabited earth seems to be necessarily going into destruction" (Hutton, 1788, p. 260). Hutton's discovery of this circular geological formation process has extended beyond the realm of geology, inspiring artists, designers, and architects who recognize the beauty and significance of this cross-scale, material-driven formation process.

Construction as an Event in Space-Time

The act of construction is typically seen as the process of assembling materials (Zumthor et al., 2015). This involves designing architectural details and hardware that join materials together, and the level

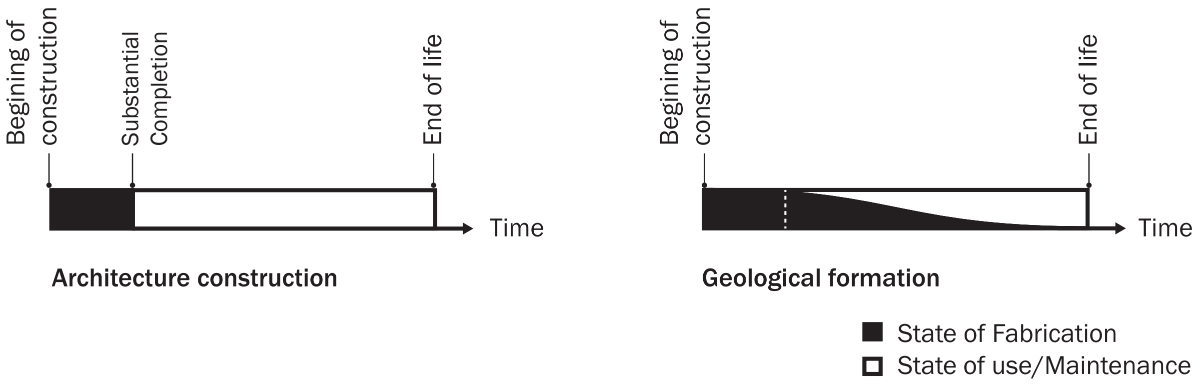


Figure 3.3.1. Continuous fabrication: Concept diagram of geological formation process that does not have a clear demarcation between the state of construction and post-construction.

Figure 3.3.2. Eroding Stool: Rock-jammed formwork was used to fabricate a concrete stool. Jammed rock falls and erodes with time. This design draws inspiration from an arch-shaped standing rock in the desert formed by the eolian process (Bottom-Left, Right). Standing rock in Tassili n'Ajjer, Algeria - Reprinted from picstatio.com, 2017 (Top-Left).

of success is often measured by the extent of assembly achieved. However, construction can also be perceived as a temporary state of matter. The Spanish artist Lara Almarcegui approaches construction as something that is 'poured' or 'delivered' rather than 'assembled'. In her work, *The Rubble Mountain*, she uses debris from a construction site to create a pile of building materials that is composed in a different way than an assembled building. The Rubble Mountain is an aleatory structure held together by friction and gravity without any predetermined form. It is a fluid mass that exists in a specific time and space. This formless concept of construction challenges the notions of permanency and accuracy in architecture.

Building as a Geological Element

It is challenging to view built structures like buildings and infrastructure as transitory collections of matter, on their way to becoming something else, as people often perceive them as permanent objects. However, it's important to remember that materials, including building materials and buildings themselves, are transient in nature. In the early 20th century, Kislinger Zerstörung claimed that buildings were living geological entities. He saw buildings as a conglomeration of elements from a broader context of geological elements. Through his close-up photographic examination, he visualized the different levels of decay in different parts of the building and juxtaposed observations of weathering in different buildings from different eras (Ricciardi & Rose, 2013). He argued that the cycle of humidity

Figure 3.3.3. Flowing Stool: The stool is formed as the liquid concrete sets and hardens, a process that draws inspiration from the transformation of flowing magma into igneous rock (Bottom-Left, Right). Flowing magma from Hawai'i volcanoes national park - Reprinted from bigislandhikes.com, 2017 (Top-Left).

and dryness is the true activator of material aging, rather than a single line of decay. In essence, the rhythm of moisture, or *"Feuchtigkeitsrhythmus,"* is the primary motivator for architecture's historicity (Allais, 2018, p. 50). Kislinger's observations provide evidence of the potential use of natural forces and material transformation as productive tools for shaping buildings that are closely linked to the geological formation.

Geomorphic Concrete

In conventional reinforced concrete construction, the physical object is expected to maintain its form and state permanently after the formwork is removed. Yet, in geological formation processes, there is no binary division between materials pre-construction and post-construction, as is the case in architectural construction. According to Moshen Mostafavi and David Leatherbarrow, the weathering of a building is a form of completion (Mostafavi & Leatherbarrow, 1993). Yet, Despite this, there persists within the architectural practice an emphasis on achieving an unattainable ideal state of construction and denying any transformation from the completed state. What could be achieved if designers embraced the natural transformation of materials, instead of trying to resist or ignore it? There are several examples of using material aging productively in architecture. While concrete is often considered as timelessness matter, Adrian Forty used the term *'untimelessness'* to describe the concept of an extended time frame of concrete from the moment of construction and future use (Forty 2013). The house and office at Stock Orchard Street in North London, designed by Sarah Wigglesworth Architects, is a perfect example of using material aging productively in architecture. The exterior wall is made up of stacked sandbags containing sand, cement, and lime mix that was wet after it was laid and set hard by weathering. The sandbag wall was designed to reveal the concrete after it hardened, and the sandbags tore away from aging. As the wall continues to age, rain and sun erode the surface of the wall and change its shape. This wall is not the result of instant curing but a long-term cycle of hardening, revealing, and eroding, which was destined from the construction method. The architects write about this wall as "a wall that has been designed to allow time to pass through it, and thereby to modify it; an evolutionary architecture" (Hill, 2001, p. 26).

Geomorphic design diverges from conventional concrete construction methods that blindly follow geometries outlined in a set of drawings. Instead, this approach allows for the creation of shapes and forms through the use of materials that change over time, presenting an opportunity to generate form through the design of materials that respond to the environment. This alternative design and fabrication concept represents a departure from the labor and energy-intensive methods employed in traditional concrete construction. By incorporating natural forces and phenomena such as gravity, wind, material phase change, and dissolution into the formation process, geomorphic design follows the example set by nature.

In the upcoming chapter, I will delve into the injection printing technology which I employed to create heterogeneous concrete. Initially, I will establish the context of injection printing technology and examine existing projects that have employed this method. Afterward, I will outline the precise steps and methods for tool and material design.

Figure 3.3.4. Anti-precision/geometry coupling: The precision of kinematic coupling is achieved by constraining the degrees of freedom of the moving axis. However, this terrain-shaped coupling system accepts more movements, such as sliding, rotating, and falling, somehow still finding its own stable position.

4 Methodology

4.1 Add-Trractive Fabrication

Digital fabrication techniques can be broadly classified into two categories; subtractive and additive fabrication. Subtractive fabrication is a sculpting process that involves removing material where it is not required to achieve the desired shape. Examples of subtractive fabrication methods include CNC milling, laser cutting, and water jet cutting. On the other hand, additive fabrication methods involve stacking or joining materials together to create a form. These methods include robotic stacking, 3D printing, and binder jetting.

The addition and subtraction of materials are not limited to digital fabrication. They are also fundamental processes found in nature. For example, landscapes are formed through the erosion (subtractive process) of deposited (additive process) sediments over time. A concept called *add-tractive* fabrication combines both additive and subtractive processes in digital fabrication and active material transformation processes. This involves adding one material into another (additive) and allowing the heterogeneous object to continue evolving through an erosion process (subtractive).

Machine fabrication has introduced a computer-controlled hybrid manufacturing process that combines additive and subtractive techniques to improve surface quality for 3D printed objects and reduce material waste during milling. However, the geomorphic concrete approach is not solely concerned with accuracy or conservation, but with creating a material that is fluid and constantly evolving. Through the integration of additive and subtractive processes, this approach invites ongoing transformation and development of the material, reflecting natural processes of change and adaptation that defies traditional material notions of concrete. The concept for this fabrication technique draws inspiration from methods that create heterogeneous material or incorporate natural agents in the process of making. Following sub-chapters review various pieces of related research, including Ice Formwork, Machine Delay Fabrication, 3D Chemical Sculpting, and injection 3D printing.

Ice Formwork

Vasily Sitnikov investigated the use of CNC-milled ice as a concrete formwork in his doctoral thesis. He emphasizes the ecological advantage of ice formwork over conventional wood formwork because the water can freeze again and be continuously reused. Beyond the ecological advantage of ice formwork, it captures the unique state of water through controlled melting. Firstly, Sitnikov CNC-milled an ice panel into the desired shape and pattern. After the milling process, he locally melted the ice to add smoothness or additional deformation to the formwork. Lastly, he poured the concrete into the ice formwork. In this controlled melting ice formwork, the concrete freezes at the unique moment of state change of water from solid to liquid (Ice Formwork, 2020). By adopting the constantly changing shape of the formwork, the concrete structure cast in ice formwork works with the range of accuracy of the computer-controlled milling technique and the behavior of ice according to temperature.

Machine Delay Fabrication

This experimental fabrication technique explores the creative use of time delay between the machine and material reaction. In general, concrete 3D printing technology faces a nontrivial problem with material transformation after printing, such as slumping, because any difference between the 3D printed form in reality and digitally designed shape is considered a failure. However, Machine Delay Fabrication embraces material transformation and discontinuous fabrication to create unique forms and textures (Cohen, 2019).

3D Chemical Sculpting

A research team at Singapore University has developed a sculpting method using volumetric material modification. The method involves injecting aluminum solution into the liquid concrete to intervene in its curing process. When aluminum reacts with water, it generates hydrogen gas, which creates voids inside the concrete. This chemical carving process is activated through an additive injection fabrication process, which can be viewed as a hybrid of additive and subtractive fabrication techniques (Chee et al., 2019).

Injection 3D Printing

Injection 3D printing is a fabrication method that extrudes material into another liquid medium. Early research on this method includes *Buoyant Extrusion* from Princeton University and *Rapid Liquid Printing* from the Self-Assembly Lab at the Massachusetts Institute of Technology. French startup Soliquid and Technische Universität Braunschweig have also used this technology to print concrete into a liquid suspension material (Xiao et al., 2022). The principle of injection 3D printing is to intrude one material into another material with a computer-controlled path. When it comes to injection 3D printing concrete, this technology can be used in three different ways (Hajash et al., 2017).

1. Inject 3D print concrete into suspension material to get line structures of extruded concrete.
2. Inject 3D print suspension material into concrete to make cavities inside of the concrete object.
3. Inject 3D print concrete into another concrete with different material properties.

Many digital fabrication methods have been tested to make heterogeneous and anisotropic materials, including programmable textiles and multi-material 3D printing. However, the process of injection concrete printing provides several technical advantages over the layer-by-layer stacking additive fabrication method. Firstly, it is not limited by gravity, as the printing of material depositions takes place directly within a liquid medium of similar density, which prevents floating or sinking. This eliminates the need for support structures, making the fabrication process simpler. Secondly, the grain direction of the print can be controlled, allowing for the creation of more complex structures with high material efficiency, while avoiding the need for complicated assembly processes. Thirdly, the fabrication time is shorter than with conventional additive manufacturing because there is no need for stacking or making supporting structures during the building process.

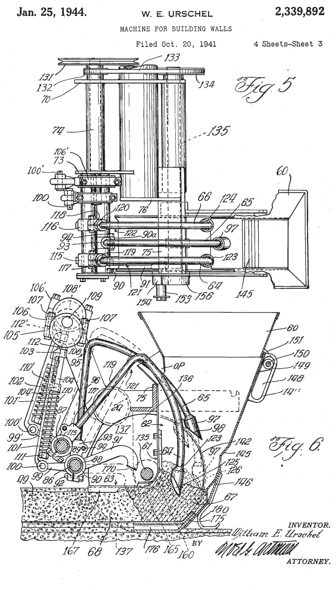
This thesis showcases three experiments that utilize the Injection 3D Printing method to create geomorphic concrete. These experiments are detailed in chapter 5, which include:

1. The injection of reinforcement materials such as high-strength concrete and metal cable into liquid lightweight concrete.
2. Inject 3D printing concrete into the sand to reveal the printed structure naturally by gravity.
3. Inject 3D printing gypsum solution as a hardening suspension material into concrete.

To provide context for these experiments in geomorphic concrete, I will initially explain the tool and material development that aligns with my design intent and vision.

4.2 Tool Design

Machines are often considered to be black boxes that produce reliable and consistent outputs regardless of the context. However, the behavior of machines is unique and depends on the context in which they operate (Negroponte, 1973). Like humans, machines are influenced by external factors such as weather, time, location, and collaborators, as well as internal specifications like size, weight, material, and force. In a complex environment like a construction site, machines must be calibrated and expected to move and operate differently than in a stable environment like a factory or laboratory. Humans are more intuitive and natural at adjusting movement and force based on their observations of the surrounding environment and the materials they handle, as Robert Trevor has stated that the human form of work provides practical and customary measurement (McVicar, 2019). He explains this by saying “Ancient measures were neither as precise nor as finely subdivided as the modern scientific measures used today because they did not need to be. At first, local surveyors marked out territories with their own strides; builders and craftsmen sized and shaped materials using the best hand tools available.” (Tavernor, 2008, p. 4). Machines, on the other hand, do not always recognize and analyze their surrounding environment and may struggle to react accordingly. This is one of the reasons why fully automated construction is difficult to be realized. However, the limitations of machines and technology allow humans to continue adding their intelligence and creativity to construction by actively participating in the making process.



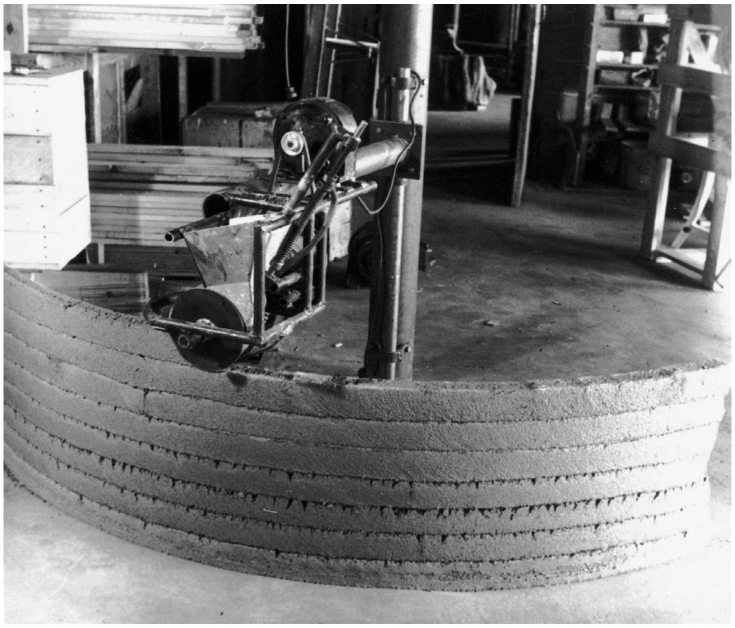


Figure 4.2.1. Machine for building walls Patent: Patent drawing of early type of 3D concrete printer, US2339892A, William E Urschel, 1944.

Figure 4.2.2. Machine for building walls: The wall building machine under operation test - Reprinted from 3dprint.com 1941.

In 1941, William E Urschel, an American inventor and entrepreneur, created a Machine for Building Walls - U.S. Patent No. 2,339,892 (Urschel, 1944). This early machine was one of the first concepts for 3D concrete printing. The device compressed and placed a mixture of cement that had been poured by humans. The machine was mounted on an axis, which directed it to stack concrete in a circular shape. This tool was semi-automated, allowing humans to intervene during the 3D printing process and create openings, adjust tooling path, and place reinforcement. Furthermore, the simplicity of the machine made it easy for humans to manipulate and control the machine's operations to adapt to uneven construction environments. Taking inspiration from Urschel's Machine for Building Walls, I created the 3D Concrete Pour-inter, a small-scale 3D concrete printing tool. Similar to a hand plane used in woodworking, the Pour-inter is a simple hand tool that can lay concrete like a 3D concrete printer, but without the need for machine power, a gantry system, or robot arms. Two people can operate the Pour-inter, with one person pushing the tool forward and the other pouring concrete into the funnel. The tool lays fiber reinforcement along the path of the concrete print.

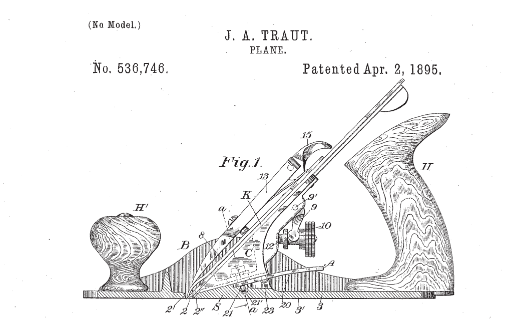


Figure 4.2.3. Plane: Patent drawing of knife adjustment for plane, US536746A, J.A. Traut, 1895.

Figure 4.2.4. Concrete Pour-inter: Hand 3D concrete printing and fiber reinforcement tool that is inspired by wood plane, and Urschel's machine.

As exemplified by Urschel's Machine for Building Walls and my own 3D Concrete Pour-inter, the aim of tool design in this project is to enable human intervention during computationally controlled fabrication. Rather than focusing on exploring human-machine interaction through advanced technologies like gesture-controlled machines or computer vision, the goal is to develop simpler mechanisms that assist humans in tasks such as removing and adjusting the extruder from a robot arm or changing material extrusion speed and direction during 3D concrete printing.

Extruder Design Overview

As I explained in chapter 4.1 Add-Tractive Fabrication, I utilized inject 3D printing technology to fabricate geomorphic concrete and built two different tools to extrude different types of materials.

1. Paste extruder for inject 3D printing gypsum and concrete.
2. Cable extruder for inject cable inside the concrete.

Both tools were attached to a 6-axis robot arm, the KR10R1100, and printed using G-Code generated from Grasshopper, which is a plugin for Rhinoceros 3D (Rhino, 2022). Prior to designing and constructing the tool, several decisions were made regarding the extruder. Firstly, I opted to mount the extruder directly onto the robot arm to minimize the distance the material had to travel. This decision was based on the Hagen-Poiseuille law, which states that the flow rate (Q) is inversely proportional to the nozzle length (L) (Vozzi et al., 2002). Consequently, a more powerful plunger force is required to push the paste through a long pipe from the extruder to the outlet nozzle. Furthermore, the tool was made small and lightweight enough to allow testing of objects that fit within the 5kg payload of the KR10R1100.

Paste Extruder

Several commercial and laboratory-scale paste extruders have been developed for clay and concrete 3D printing. In my geomorphic concrete fabrication project, I utilized two paste extruders. The first one was a custom-built plunger type design, inspired by the open-source clay extruder design of CERA-1 and the extruder design from MIT M.Arch thesis MORE OR LESS EXACT by Dalma Földesi and Jung In Seo (Földesi & Seo, 2020). This extruder operates with a 30:1 ratio worm gear connected to a Nema23 stepper motor, which moves the lead screw to push the plunger and extrude loaded gypsum paste or fine concrete paste through a 5mm or 9mm inner-diameter nozzle. The extruder was designed to allow easy material loading and unloading, as well as simple mounting and demounting onto a 6-axis robot arm. The 2040 aluminum extrusion profile spine structure enables the extruder to be adjusted and demounted from the 6-axis robot arm without requiring a tool-changing operation from the robot. The second paste extruder I used was the 1000ml Linear Actuator Ram, a commercial product specifically designed for clay 3D printing.

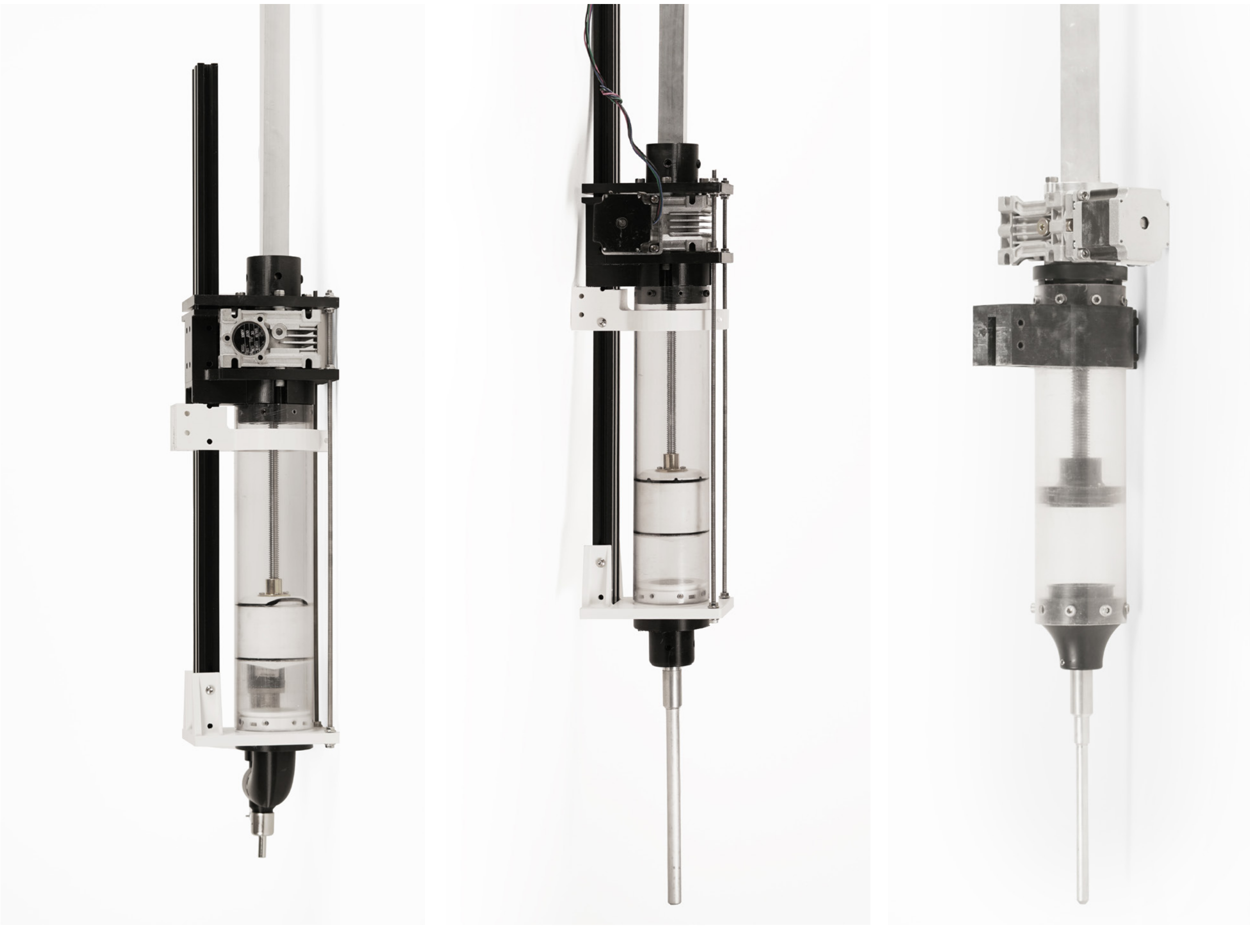


Figure 4.2.5. Paste extruders: Paste extruder made by the author with auger (Left), Paste extruder made by the author with 9mm diameter nozzle (Middle), 1000ml Linear Actuator Ram with 5mm diameter nozzle (Right).

Cable Extruder

In addition to utilizing materials like fine concrete and plaster mix to inject 3D printing into the concrete, I have developed the application of metal cables to be injected into concrete. To create this tool, I began by analyzing and modifying a 3D printer filament extruder. The resulting cable extruder is equipped with a Nema17 stepper motor connected to a 1:5.18 ratio planetary gear, which enhances its torque, and four interconnected gears to enhance its gripping force by applying rotation of rollers from both sides of the cable.

The cable extruder functions by feeding a 3/8” diameter wire from the top of the tool and extruding it through a long nozzle, enabling the delivery of metal cable into liquid concrete. The speed of the wire feed can be regulated by adjusting the potentiometer knob of the controller. This tool was utilized for the Cable Deposition Reinforcement project, which is detailed in Chapter 5.2.

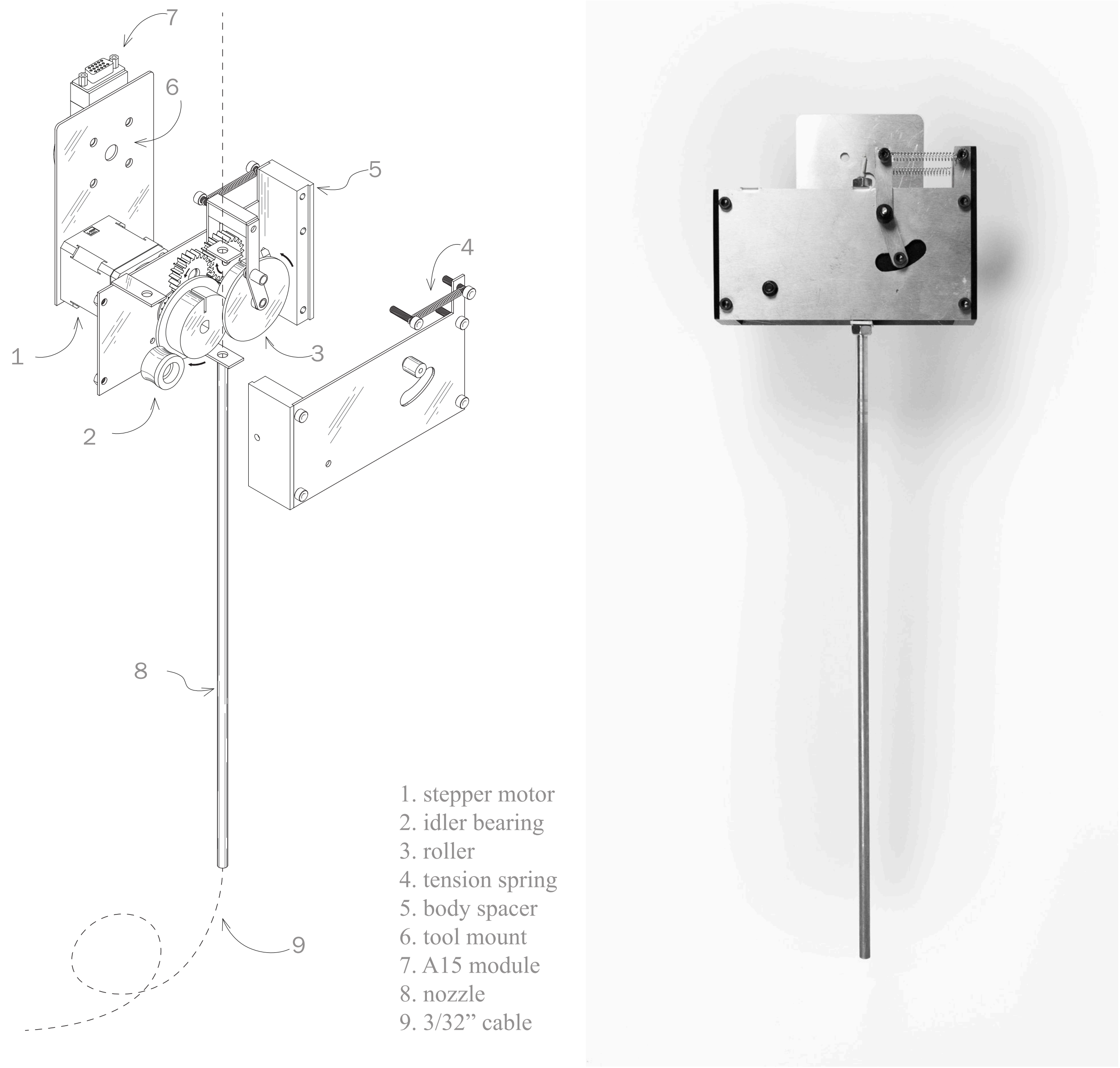


Figure 4.2.6. Metal cable extruder: This tool extrudes a 3/32” diameter cable into liquid concrete.

Controller

The primary goal of the controller design is to enable effortless human intervention in the computational fabrication process with simple human-friendly controls, including turning knob and push buttons. This control box enables users to easily adjust the material extrusion rate, pause and resume printing, and retract the plunger to unload materials from the extruder. The extrusion rate can be controlled by turning the 100k ohm potentiometer knob (material extrusion rate varies based on viscosity and density). The start and stop button, located near the edge of the PCB, allows users to pause and resume printing. On the inner side of the PCB, a reverse button is positioned to change the direction of plunger movement. To ensure easy and reliable connections of electric components, I designed an Arduino UNO breakout board using the open-source PCB design software KiCad and milled it with a Roland SRM-20 milling machine. For the future needs, the breakout board has extended pin connections to digital pins, making it easy to incorporate additional input or output devices.

Figure 4.2.7. Controller version 1.

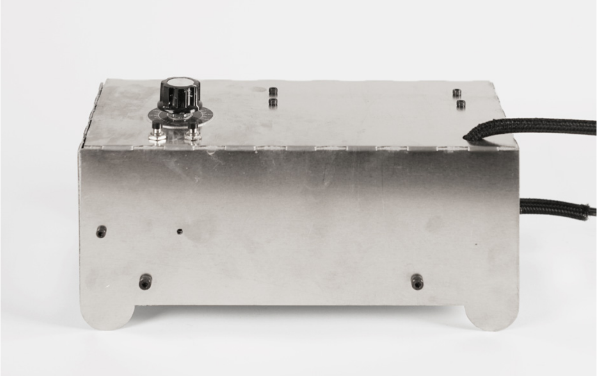


Figure 4.2.8. Controller version 2.

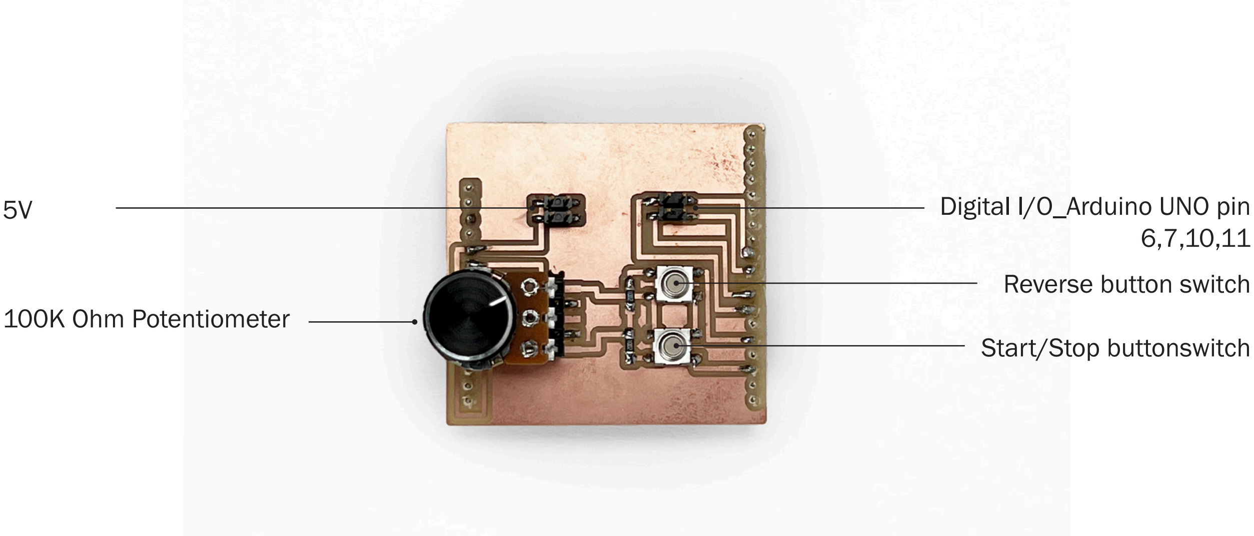


Figure 4.2.9. Breakout board: This board enables the Arduino UNO to connect to potentiometer and push buttons through its digital I/O pins. Additionally, it facilitates the connection of a stepper motor driver and power to the Arduino.

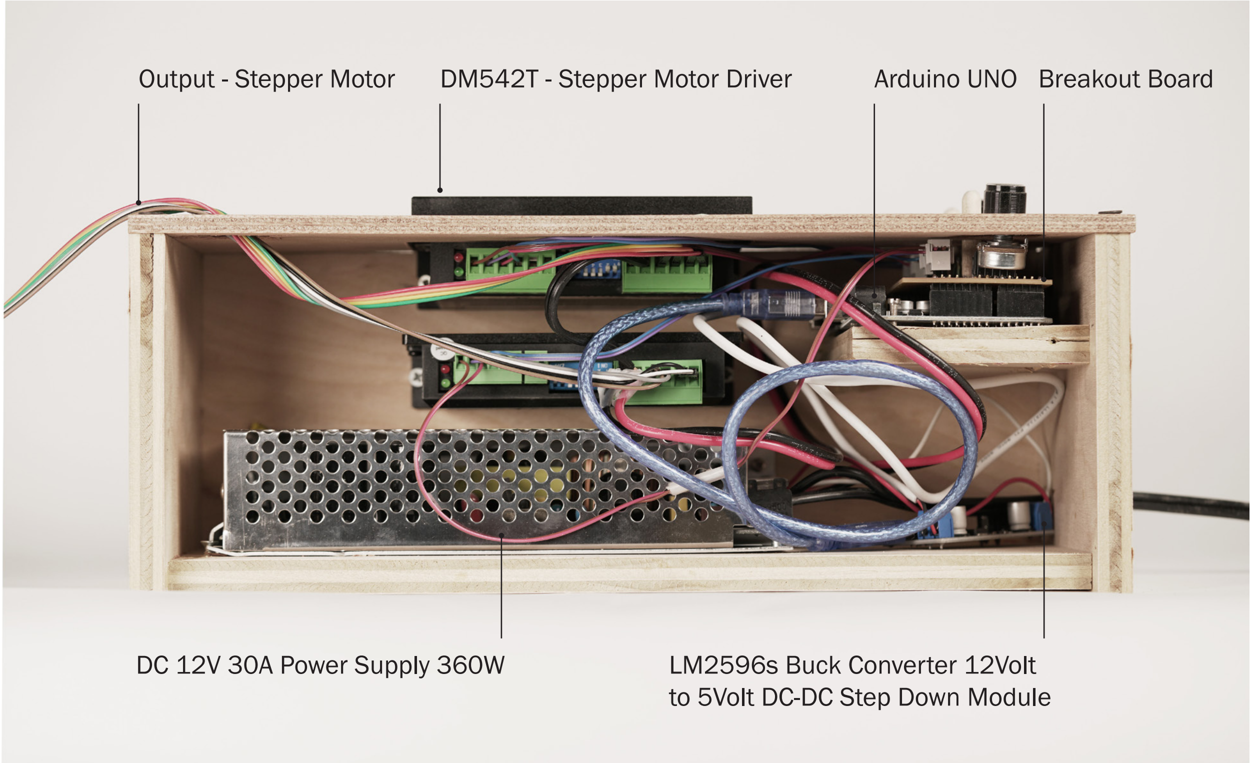


Figure 4.2.10. Inside of the controller version 1.

Kinematic Tool Mount

As the tool design evaded making a hose connection from the material source to the nozzle, which decreases the flow rate, the plunger-style extruder is required to mount directly to the 6-axis robot arm. In this tool design, the extruder is required to be unloaded from the manipulator (robot arm) to change materials. To simplify and expedite this process, I created a kinematic mount detail that can be securely fixed using a simple pin connection. This detail enables faster and easier material change.

Figure 4.2.11. Connection detail for easy tool change: The tool's connection mechanism is specifically crafted for effortless mounting and dismounting from the 6-axis robot arm. It is possible to change tools by simply inserting the tool into the duck-tail joint host, which is linked to the robot arm.

4.3 Material Design

3D Printable Paste

The main challenge in designing materials for paste 3D printing is achieving the appropriate viscosity. During initial tests, several experiments resulted in damaging the extruder due to the printing material becoming rammed inside the tube and yilded the lead screw that pushes the plunger. According to research on printable materials, there are a few critical principles for 3D printable paste, such as pumpability, extrudability, buildability, and open time (Rehman & Kim, 2021). These principles are general guidelines for printable material design, but the material properties of the paste can be customized based on the intended use. In this project, the injection 3D printing paste mix is less affected by buildability because the material is delivered into a liquid or granular medium. However, other principles are critical for the limited extrusion tools I utilized.

Numerous studies have been conducted on printable concrete mixtures. For instance, research led by T. T. Le on 3D printable concrete mixtures concludes that a mixture of 70% cement, 20% fly ash, and 10% silica fume, with a water-binder ratio of 1% superplasticizer is ideal (Le et al., 2012). However, the optimized material design varies based on extruder design, printing context, use of lubricant layer, and printing methods. Through empirical research, I have developed three different mixtures for geomorphic concrete fabrication. These mixtures are not optimized for a general situation but rather designs that have yielded consistent results in my specific fabrication process. For printable gypsum paste, I have used the GYP-230226-3 mixture for fast dissolving and eroding suspension material. The CON-230222-1 mixture is ideal for injection 3D printing concrete into sand and lightweight concrete, while the AIR-230306-2 mixture is designed for casted lightweight concrete, which serves as a medium for concrete injection printing.

Specimen No.	Plaster	Water	Cement	Plasticiser	Deflocculant	Fine aggregate	FM160
GYP-230226-3	2.00	0.90	-	-	1.00	-	-
CON-230222-1	-	0.30	1.00	0.01	-	1.00	-
AIR-230306-2	-	0.80	1.00	-	-	1.00	0.01

Figure 4.3.1. Mixture ratio: The material mixture proportions that are employed in the production of geomorphic concrete.

Gypsum Morphology

After discovering a printable material mix formula via extrusion tests, I conducted an experiment to regulate the erosion rate of a gypsum-based suspension material. Geomorphic concrete introduces a new concept of creating concrete objects that can evolve over time, akin to sedimentary rock's formation via differential erosion rates of its components. The 3D printed gypsum paste functions by dissolving the binder upon contact with water and sand particles, resulting in erosion through the effects of gravity, water flow, and wind. To enable to design the erosion process of concrete, controlling the water solubility of the gypsum-based suspension material is crucial. Gypsum's solubility in pure water at 20°C is 2.531 g/L, making it an optimal suspension material for geomorphic concrete that aims to shape within architectural timescale. This solubility is lower than salt (360g/L) but higher than calcium carbonate (1.5 mg/L) (Klimchuk, 1996). To decrease the material's solubility, my proposal is to add Portland cement to the mix.

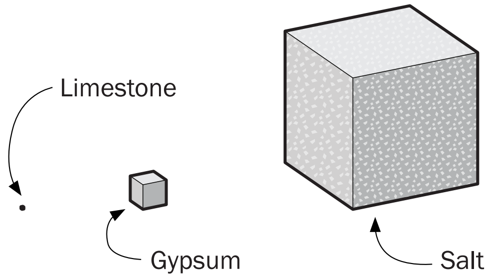


Figure 4.3.2. Solubility comparison diagram: Each cube in the diagram represents the amount of mineral that can dissolve in the same quantity of water.

Erosion Test

The erosion test aimed to compare the erosion rate of three different specimens with varying plaster to cement ratios. The specimens, 50 mm diameter and 60 mm tall cylinder, were subjected to falling water at a rate of 40 g/s from 150 mm distance. My hypothesis was that the more cement added to the mix, the less soluble and more durable it would become. However, the test failed to establish a formula that explains the relationship between cement admixture and erosion rate. This was due to the insufficient subdivision of the test mix ratio, which made it difficult to measure erosion rate accurately.

The gypsum mix without cement admixture (GYP-230414-1) eroded too quickly, and the erosion of the gypsum mixes containing 2% and 5% cement (by weight) could not be measured meaningfully. However, I did observe the specimen caved in about 7.5 mm after 14 days of the test. There were no observable

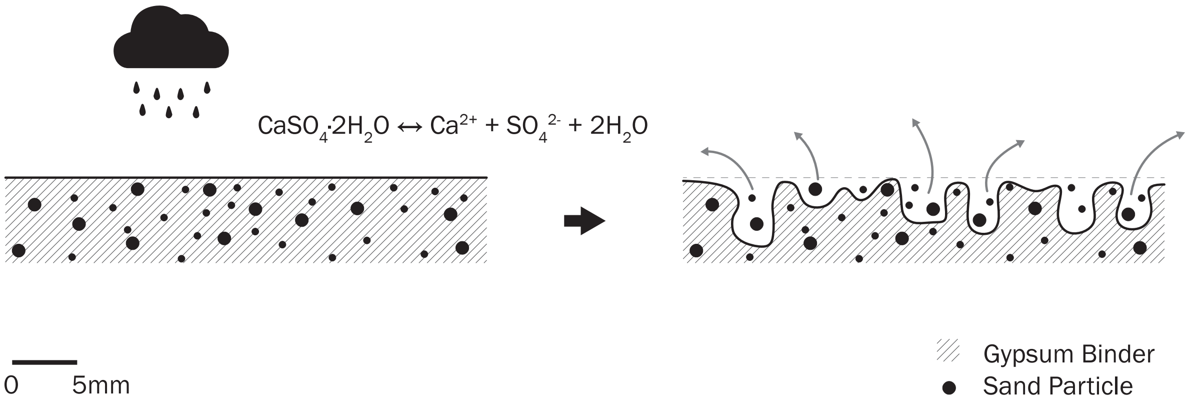


Figure 4.3.3. Erosion diagram: The erosion process of gypsum mixture that has inject-printed into the concrete.

Specimen No.	Measurement	Plaster	Water	Cement	Plasticiser	Fine aggregate
GYP-230414-1	Ratio	2.00	0.90	0.00	0.00	2.00
	Weight (g)	250.00	112.50	0.00	0.00	250.00
GYP-230414-2	Ratio	2.00	0.90	0.05	0.01	3.00
	Weight (g)	198.02	89.11	4.95	19.60	297.03
GYP-230414-3	Ratio	2.00	0.90	0.10	0.02	4.00
	Weight (g)	163.93	73.77	8.20	14.75	327.87

Figure 4.3.4. Erosion ratio for erosion test: The ratio of material mixtures used for the erosion test on three specimens.

changes in the gypsum mix with 5% cement admixture. It is still too early to draw any conclusions about how cement admixture affects material erosion and strength. However, this test suggests that cement admixture could play a role in controlling the erosion speed of geomorphic concrete.

In addition to conducting erosion tests using casted specimens, I performed extrudability and printability tests on the same gypsum mixtures. The purpose of this test was to evaluate whether the gypsum mixes were suitable for use as injection 3D printing material with the plunger-style extruder that I employed. This test also assessed the viscosity and curing time of the material, to determine if it was applicable for 3D printing. Although there were minor differences in viscosity and curing time among the three materials, all three were successfully 3D printed and maintained their shape without slumping or clogging inside the extruder.

Material specifications

- **Gypsum:** solution grade gypsum_Calcium Sulfate Dihydrate ($CaSO_4 \cdot 2H_2O$) 97%
- **Cement:** Portland cement type I
- **Fine aggregate:** Quikrete play sand screened with 1mm screen
- **Superplasticizer:** Basf, Melflux 2651F, concrete additive water reducer
- **Deflocculant:** darvan #7

Fluid Concrete for Injection 3D Printing Medium

In order to inject secondary material into poured concrete using injection 3D printing method, it is necessary to design the concrete medium that maintain its liquid state throughout the injection process. To achieve this, I incorporated both a retarder and superplasticizer in the concrete mix. The retarder slows down the setting process, while the superplasticizer acts as a water reducer, reducing viscosity without the need for additional water. Although increasing the water content of the mix can produce a similar result, it can also adversely affect the concrete's strength. The fine concrete mix I utilized for fabrication is stated in Figure 4.3.1 (CON-230222-1).

Figure 4.3.5. Printability test: Extrudability and buildability test for gypsum mixture.

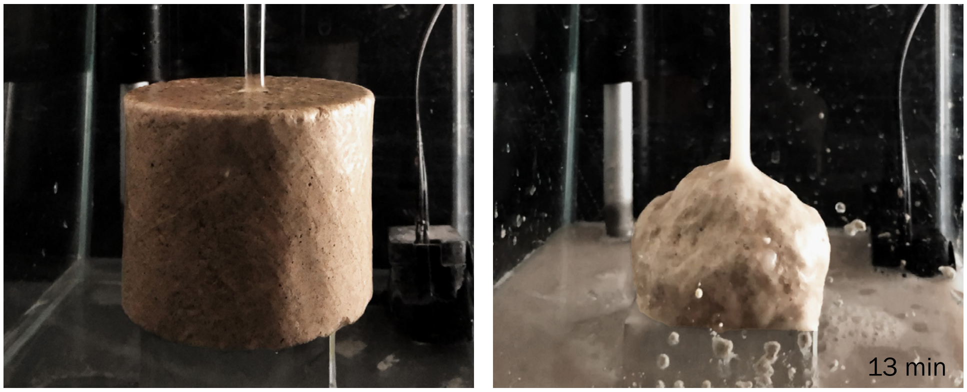


Figure 4.3.6. Erosion test - GYP-230414-1: The specimen completely eroded within 15 minutes.

Figure 4.3.7. Erosion test - GYP-230414-2: After a 14-day test, a specimen's surface exhibits a pavement depth of 3.75mm. The image on the right represents the pavement from 3D scanned model.

4.4 Injection 3D Printing

In Chapter 4.1, a comprehensive analysis of prior studies and manufacturing techniques relevant to the production of geomorphic concrete was conducted. Chapters 4.2 and 4.3 delve into the intricate details of the tool and material design employed in this thesis. In this chapter, a thorough, step-by-step account of the geomorphic concrete fabrication process will be presented, alongside an explanation of any technical terms used in the fabrication guidelines.

Technical terms that used in this thesis:

- **Extruder:** A paste extrusion tool capable of being mounted on a 6-axis robot arm or used as a handheld device.
- **Injecting material:** The substance that is extruded through the extruder. In the context of Injection 3D Printing, the injecting material is extruded into the medium material. For the injection material, I utilized either fine concrete mix or gypsum mix. Details of mix ingredients and ratios are stated in Figure 4.3.1.
- **Medium material:** The substance that is poured into a mold and acts as a medium for the injecting material or fluid formwork. I used slow-curing concrete as a medium material to inject 3D print gypsum paste, lightweight concrete as a medium material for injecting high-strength concrete, and fine particle sand as a medium material for Inject 3D Printing concrete.
- **Injection rate:** The amount of material that is extruded per unit of time.
- **Tool path:** The route that the extruder nozzle follows along a specified line. This path is computationally generated and operated by 6-axis robot arm.

1. Design tool path and simulation

The first step in geomorphic concrete production involves envisioning the material's life cycle, including when and how it should be transformed, and what material properties should be incorporated. This approach focuses on programming the material to hold more information and react to external stimuli, rather than simply creating a finalized shape of an object. In order to achieve this, computational fabrication techniques were used to 3D print gypsum formwork and inject 3D print gypsum mix into the concrete for future erosion. The project utilized two 6-axis robot arms, namely the KR10R1100 and UR10, to move the extruder along the tool path. The tool path's G-Code was generated and simulated by Rhinoceros 3D Grasshopper applications. Two applications I mostly used were KUKA PRC by Robots in Architecture and ROBOTS by Visose.

2. Mixing and Loading Material

To carry out injection 3D printing, two distinct substances are required: the injecting material and the medium material. To ensure that both materials are utilized within a specified time frame, I created a mixture of the two substances before adding water. First, I mixed the injecting material and loaded it into the extruder, either directly into the tube or through a funnel. Then, while the tool was upside-down material loading position, I capped the nozzle after loading the injecting material. Next, I moved the

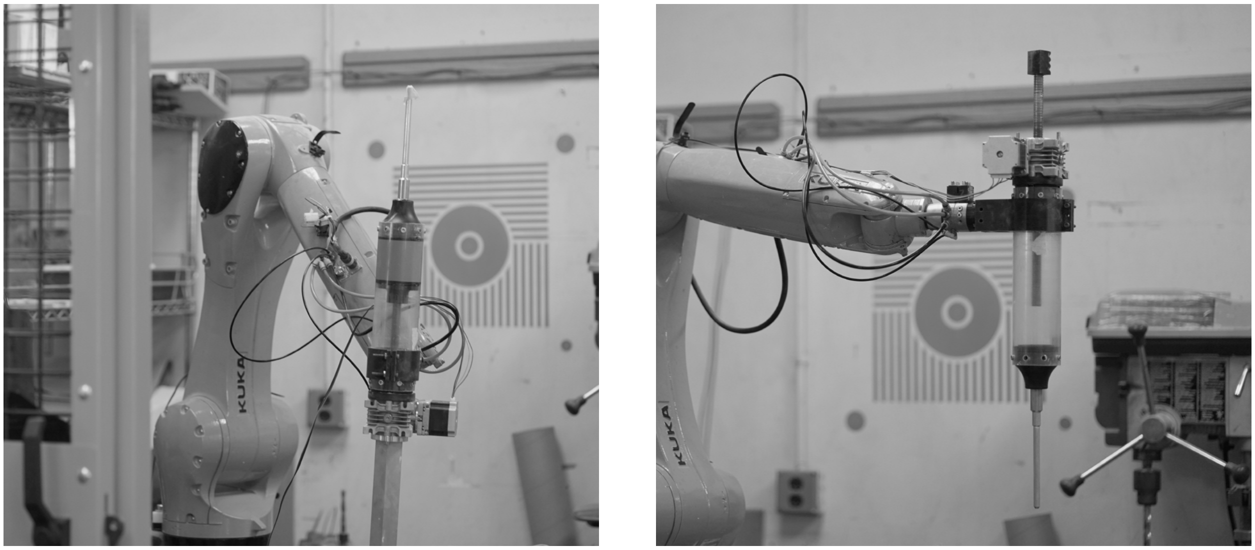


Figure 4.4.1. Loadting paste material: Paste extruder mounted to the 6-axis robot arm with material loading position (Left), Paste extruder in 3D printing position (Right).

extruder to the operating home position. After the extruder was positioned and ready to operate, I started mixing the medium material. It was important to consider the curing time of medium material to finish the injection process before the medium material solidifies.

3. Printing

After loading the injecting material into the extruder and pouring the medium material into the mold, the robot arm and extruder can be activated. The extrusion of the injection material into the medium material occurs automatically, during which I am able to control the injection rate, pause or resume injection, and adjust the printing speed through the control box. This adaptable system allows the fabricator to customize the machine's operation based on the material's behavior and context.

In the experiments in this thesis, I used two different sizes of aluminum nozzles: a 9mm Inner-diameter nozzle with a length of 241.8mm and a 5mm inner-diameter nozzle with a length of 210.8mm. Although these nozzle sizes limit the fabrication of larger architectural elements, it is still possible to create various widths and shapes of 3D printed lines by reducing the print speed and increasing the material injection rate.

Figure 4.4.2. Injection 3D printing in tube mold: Injection 3D printing gypsum mixture into the liquid concrete with a 5mm inner-diameter nozzle.

—— Straight Line Print

- - - Dash Line Print

Figure 4.4.3. Injection 3D printing line types: It is possible to print gypsum and concrete paste in either continuous lines (Left), or in discrete dashes or dots (Right).

5mm diameter print

9mm diameter print

Figure 4.4.4. Printing result of two nozzles: The image on the left showcases concrete printed through a 5mm diameter nozzle, while the image on the right displays the extruded material produced by a 9mm diameter nozzle.

Figure 4.4.5. Intersection point: To ensure the stability of the intersection of more than two prints, additional materials can be extruded. Similarly, the technique can also be applied to secure the point where the tool is turning.

4. Aging and evolving

After going through the Injection 3D Printing process, it is necessary to keep the resulting object inside the mold until it is completely cured. The duration of the curing process varies depending on the specific material mix ratio. In my experience, I usually wait for seven days before taking the material out of the mold. However, with geomorphic concrete, the removal of the formwork does not mean that the fabrication process is over. The cured material is poised to undergo a evolution process, as it is exposed to elemental forces. Over time, the object will undergo a gradual erosion process and transform accordingly.

Figure 4.4.6. Injection 3D print with various widths: Left picture displays the gypsum injection captured in a concrete cut, while the right image shows a cross-sectional view of a 3D scan of the same object. The extrusion process begins by depositing gypsum from the base and moves upwards, with the retraction speed altering. The nozzle used has a diameter of 9mm, and it initially moves at a speed of 20mm/s. The speed gradually reduces at a rate of 0.14mm/s² until it reaches a final tool path speed of 6mm/s.

Figure 4.4.7. Spiral cavity: A spiral-shaped cavity was formed inside a concrete cylinder by injecting and printing gypsum in a spiral pattern.

5 Design

5.1 Design Overview

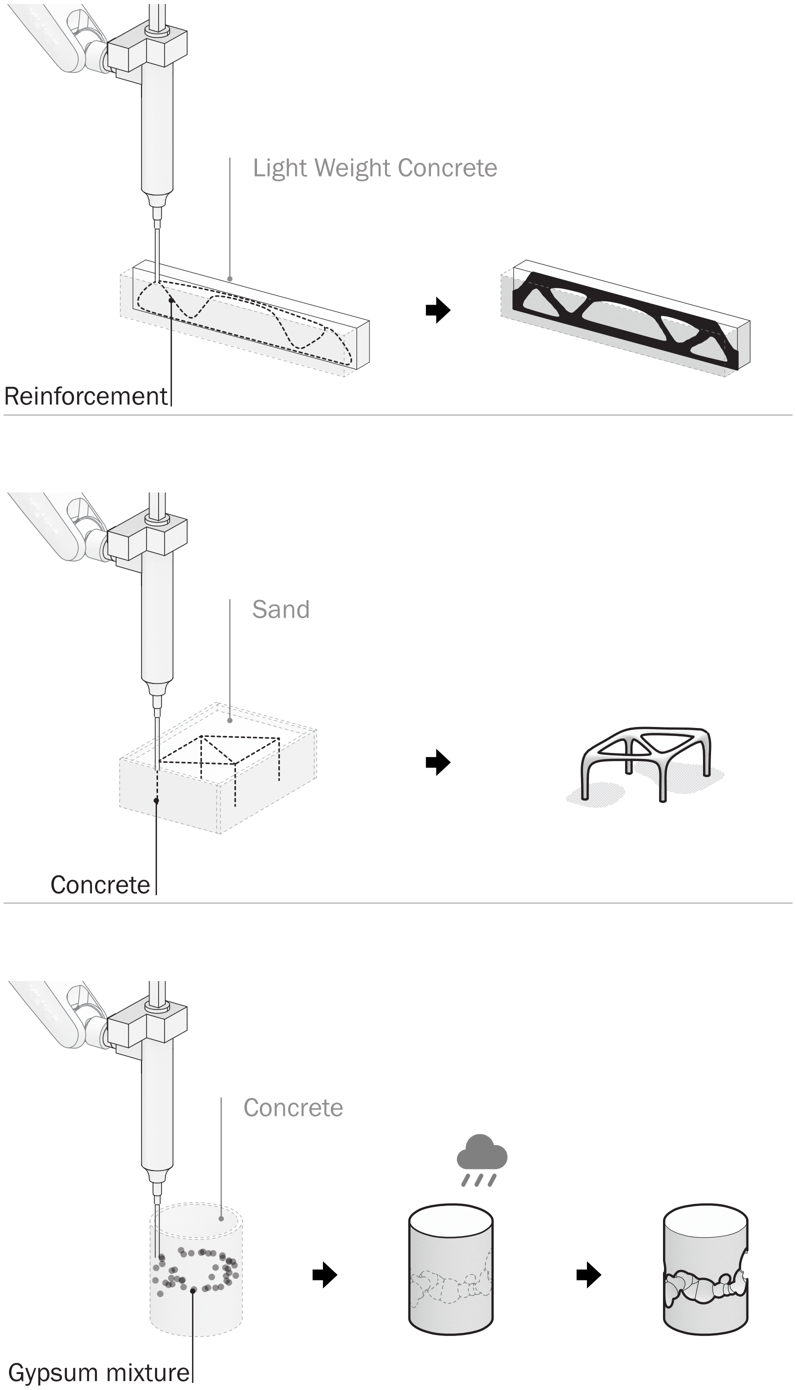


Figure 5.1.1. Three design cases of geomorphic concrete.

1. Intrusion for Performance

The injection of reinforcement materials such as high-performance concrete and metal cable into liquid lightweight concrete.

2. Erosion for Demolding

Inject 3D printing concrete into the sand to reveal the printed structure naturally by gravity.

3. Dissolution for Forming

Inject 3D printing gypsum solution as a hardening suspension material into concrete.

5.2 Intrusion for Performance

Thwarted Dream of Optimization

The implementation of generative design techniques such as shape optimization and topology optimization holds immense potential in transforming architectural design by creating more efficient and expressive concrete structures. However, fabricating complex reinforced concrete structures derived from these generative design processes can be a challenging task. For instance, if one were to construct a topology optimized beam using conventional wood formwork, there would be several obstacles to overcome. One such challenge would be to communicate the intricate geometry of the structure to the fabricator. While it is relatively straightforward to convey the dimensions and geometries of conventional building components with simple geometric shapes, transferring the design of a unique and complex structure, which cannot be easily represented in traditional drawing forms like plan, section, and elevation, can be challenging for both the architect and the fabricator. The fabrication of formwork itself presents an even greater challenge. Even if the fabricator comprehends the intricate form of the optimized concrete structure design, creating the delicate geometry, which was generated without taking into account the fabrication process, can result in excessive consumption of skilled labor and material resources to bring the generative design to fruition.

In order to address this issue, there has been a growing interest in utilizing digital fabrication such as direct 3D printing of concrete and 3D printed formwork to fabricate complex shapes designed through generative design. However, each approach has its own strengths and weaknesses. Direct 3D printing of concrete structures can offer advantages such as faster construction and greater material efficiency due to its simple fabrication process (Mechtcherine et al., 2019). However, challenges such as difficulty in reinforcement and weak interlayer bonding strength still need to be improved (Marchment et al., 2019). For instance, the Ghent University research team faced the issue of having to reinforce their topology optimized 3D-printed concrete bridge with post-tensioned cable and casted concrete inside the void space of the 3D printed structure (Ooms et al., 2022). On the other hand, the 3D printed formwork approach has the potential to achieve the same strength as conventionally casted concrete, but also presents its own set of drawbacks. For instance, this method can have a complicated fabrication process, generate waste from the formwork, and pose challenges during the demolding process (Jipa et al., 2018).

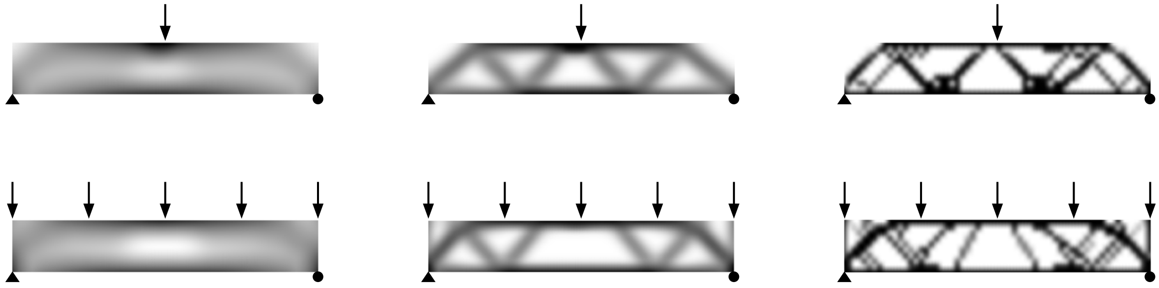
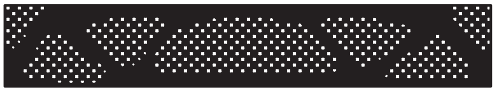


Figure 5.2.1. Topology optimized beam design from two scenarios.

Fabricating Topology Optimized Shape

- Multiple steps to fabricate
- Difficult to utilize digital fabrication
- Difficult to assemble with other components



1. Inject High-Strength Concrete
into Light-Weight Concrete

2. Create Cavities Inside of Concrete

- Simple fabricate process
- Easier to utilize digital fabrication
- Easier to assemble with other components

Figure 5.2.2. Alternative fabrication method for topology optimized structure: Topology-optimized structures generated by generative design can be challenging to manufacture due to their intricate forms. To address this issue, I propose a new fabrication method that involves selectively adding or removing materials using injection 3D printing technology. This approach aims to preserve the simplicity of the structure's shape while enhancing its performance through generative design.

Alternative Approach for Fabricating Topology Optimized Design

Rather than attempting to fabricate the delicate shapes of topology optimized designs, I propose an approach that maintains the prism shape of a structure while enhancing its performance by introducing reinforcement material into the concrete in a topology optimized manner. This method is less wasteful and simpler to fabricate when compared to directly manufacturing topology optimized geometries. Inspired by the geological process of igneous intrusion, where magma is transported and stored within the Earth's crust, resulting in complex structural characteristics, I fabricated a low-resolution topology optimized beam by injecting a secondary material into concrete to fabricate topology optimized concrete structure. This method is based on the Concrete in Concrete (CiC) injection 3D printing technique (Elias & Alderton, 2021). By mimicking the process of igneous intrusion, my method involves introducing reinforcement material into the concrete to create complex structural characteristics, ultimately enhancing the performance of the structure. To test this approach, I applied it to three different design cases: injecting high-strength concrete into lightweight concrete, injecting water-soluble gypsum mixture into regular concrete, and injecting coiled metal cable for reinforcement.

1. Inject High-Strength Concrete into Lightweight Concrete

The experiment began with generating a topology optimized design to create a 6:1 length to height ratio beam design using the Grasshopper application TopOpt. Two loading scenarios were tested, one with a point load applied to the center of the beam and the other with a distributed load applied along its length. Although the distributed load case was chosen as the design, it is important to note that the design may vary depending on factors such as variables, objectives, constraints, and loading scenarios.

To achieve the objective of injecting 3D printed high-strength concrete into the lightweight concrete (AIR-230306-2), a tool path was generated based on the 2D topology optimized beam design. The purpose of this experiment was to demonstrate that the printed shape could be preserved without sinking

Figure 5.2.3. Igneous intrusion: The process of igneous intrusion results in the formation of various grain orientations and strength variations within the host rock. The photograph depicts a dike, which is a vertically intruded magma, located in Makhtesh Ramon, Israel - Reprinted from Andrew Shiva, en.wikipedia.org, 2016.

Figure 5.2.4. Locally reinforced topology optimized beam: The darker sections of the beam are injected with high-strength concrete, while the brighter portions are cast with lightweight concrete. Unlike formwork methods, the material used for injection 3D printing is not wasted but remains within the injected concrete.

or floating when printed into a material with a different density. A similar fabrication approach was tested by Norman Hack but with identical materials for medium and injecting materials (Hack et al., 2020). In this topology optimized beam fabrication, the high-strength concrete, which is injected printed, supports most of the structural stress in the design, while the lightweight concrete acts as a medium to inject print the high-strength concrete and maintain the beam in a prism shape, making it easier to assemble with other structural components. Future work on this idea can focus on fabricating and injecting 3D printed beams with high-strength concrete and performing flexural testing to determine their strength and durability.

2. Create Cavities Inside of Concrete

Most 3D printed formwork for optimized structures are challenged by fabricating formwork and removing formwork from the casted concrete object. However, this approach involves injection 3D printing suspension material into concrete to carve the concrete to the desired shape. Unlike previously introduced projects that reinforce concrete structures locally, this method selectively removes materials from areas that do not bear loads, achieving the same goal. Using the same topology optimized beam design as the Inject High-Strength Concrete into lightweight Concrete fabrication, I generated a tool path to inject 3D print gypsum mixture (GYP-230226-3) into areas where structural material is not needed. Once the gypsum dissolves and erodes, the concrete takes on a shape that closely resembles the optimized design. The resulting beam (Figure 5.2.6) has a cavity that penetrates the cross section, but gypsum can be used to create more complex hollow structures inside the concrete beam. Alternatively, lightweight concrete can be injected into the concrete, skipping the evolving process and generating an optimized structural elements by creating heterogeneous concrete.

Figure 5.2.5. Locally material removed topology optimized beam - Before erosion: This image depicts the beam prior to the removal of the gypsum material

Figure 5.2.6. Locally material removed topology optimized beam - After erosion: This image illustrates the result after the gypsum was exposed to water and eroded away. The gypsum mixture was specifically injected in areas where the generative design determined that the material was unnecessary. The beam could be fabricated to express an optimized design or hidden inside the prismatic shape.

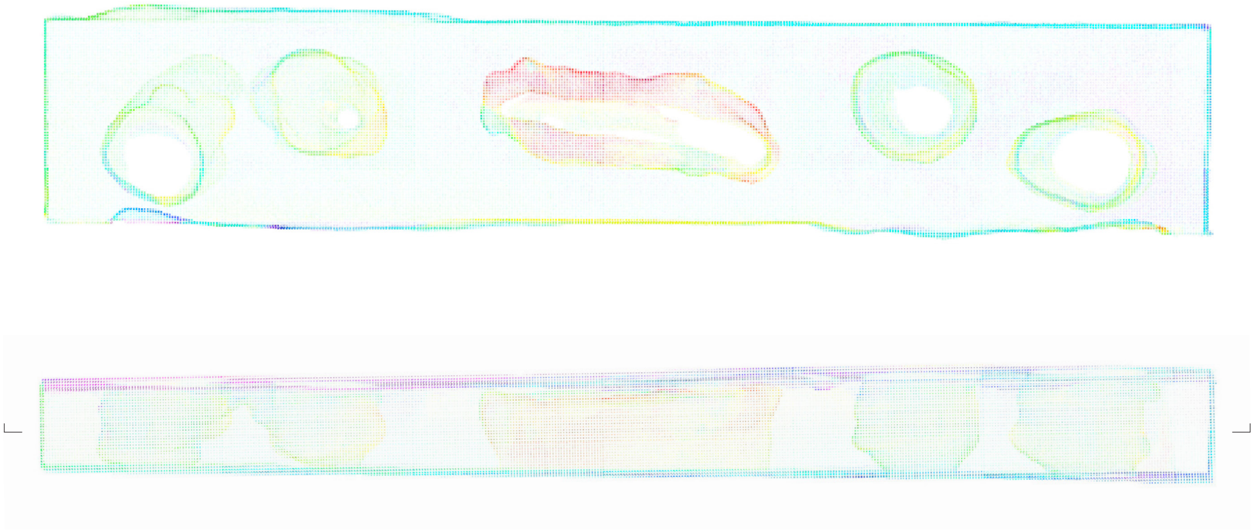


Figure 5.2.7. Locally material removed topology optimized beam - 3D scanned: The longitudinal section (Top) and plan (Bottom) of the optimized beam, which has been selectively carved, closely resembles the topology optimized design(Figure 5.2.1.).

3. Cable Deposition Reinforcement

The ability to reinforce concrete is a crucial aspect of modern construction as it enables the creation of large-scale structures. However, this feature also contributes to the high cost of construction and the emission of more carbon dioxide due to increased cement consumption. The process of fabricating reinforcement cages adds an extra step to the construction process, resulting in longer construction schedules and a greater need for labor.

Additionally, the size of coarse aggregates used in concrete is limited by the design of the reinforcement, as larger aggregates may become stuck between rebars, leaving void spaces where the concrete cannot flow. The aggregate size of the concrete mix is defined by rebar spacing, and using finer aggregate requires more cement to generate the same volume of concrete. Since cement content is responsible for a significant portion of carbon emissions from concrete, with estimates as high as 88%, traditional reinforcement fabrication leads to excessive carbon emissions during construction (Nisbet et al., 2002). If it is possible to inject flexible metal cable as a reinforcement directly into casting concrete, it is likely to make concrete construction faster, require less labor, and reduce carbon emissions by using larger aggregates in the concrete mix, which leads to less cement consumption.

The cable deposition reinforcement method has been developed by the Self Assembly Lab project in collaboration with Kimball Kaiser and En-Han Thaddeus Lee, which was inspired by Chloe Nelson-Arzuaga's research on fiber-reinforcement on additive concrete construction (Nelson-Arzuaga, 2021). The contribution of this fabrication process includes developing a method of injecting metal cable directly into liquid concrete in a desired reinforcement pattern.

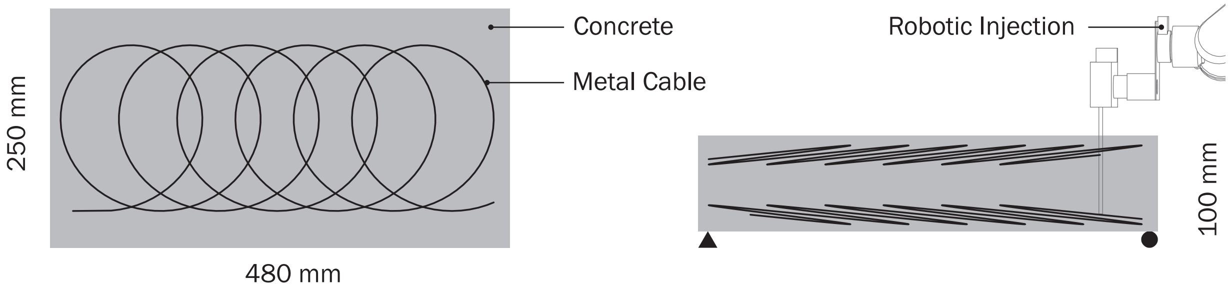


Figure 5.2.8. Cable printing design inside of concrete slab: Plan drawing (Left), Section Drawing (Right).

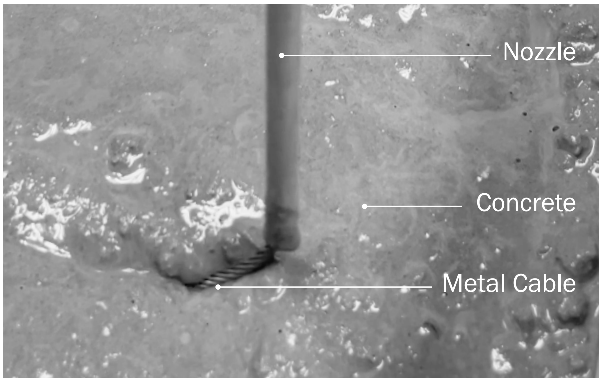


Figure 5.2.9. Metal cable printing in operation: In this close-up photo, a metal cable is being extruded through a lengthy nozzle, enabling its deposition at a depth within the concrete.

The initial specimen produced using this method was a 480 x 250 x 100mm size concrete slab with 4000 psi compressive strength High Strength Pre-mix Concrete (50 lb bag). 0.16lb of 3/32” diameter stainless steel-coated metal cable was injected into the concrete with a series of 5-3/4” diameter circles that overlapped 3-1/2”. Two layers of circle-patterned cable were printed an inch above the bottom and an inch below the top surface of the specimen. In comparison, the control specimen was reinforced with 4.3lb of 1/2” diameter #4 standard rebar, placed an inch above the bottom surface of the sample. After 28 days of curing, the specimens underwent a three-point bending test, which showed that the cable-reinforced specimen failed multiple times instead of showing a single failure like the control specimen. This result suggests that metal cable reinforcement could behave like a shear-reinforced structure, which could be safer in fatal cases.

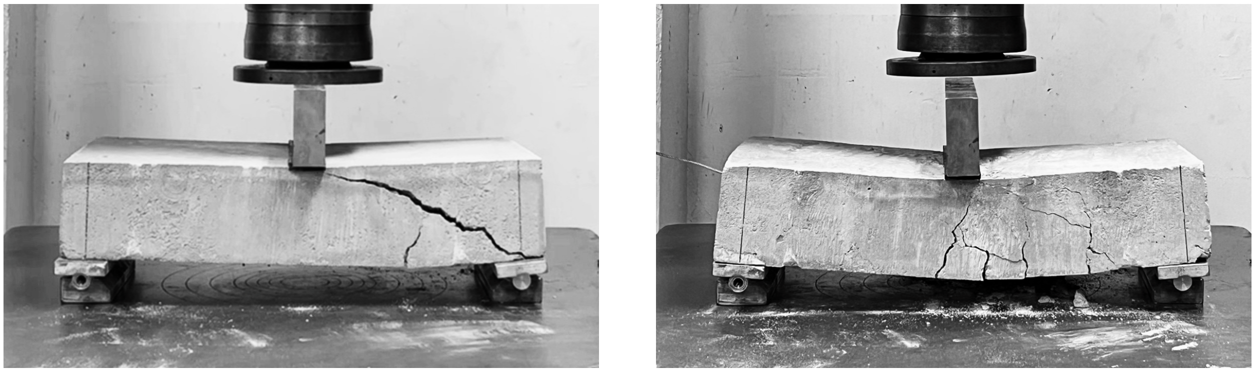


Figure 5.2.10. Three point test: The control specimen that was reinforced with half-inch diameter (Left). The test specimen that was reinforced with an inject printed cable (Right). The test result indicates that the cable-reinforced specimen had numerous small cracks, while the control specimen had a large crack that ran across the beam.

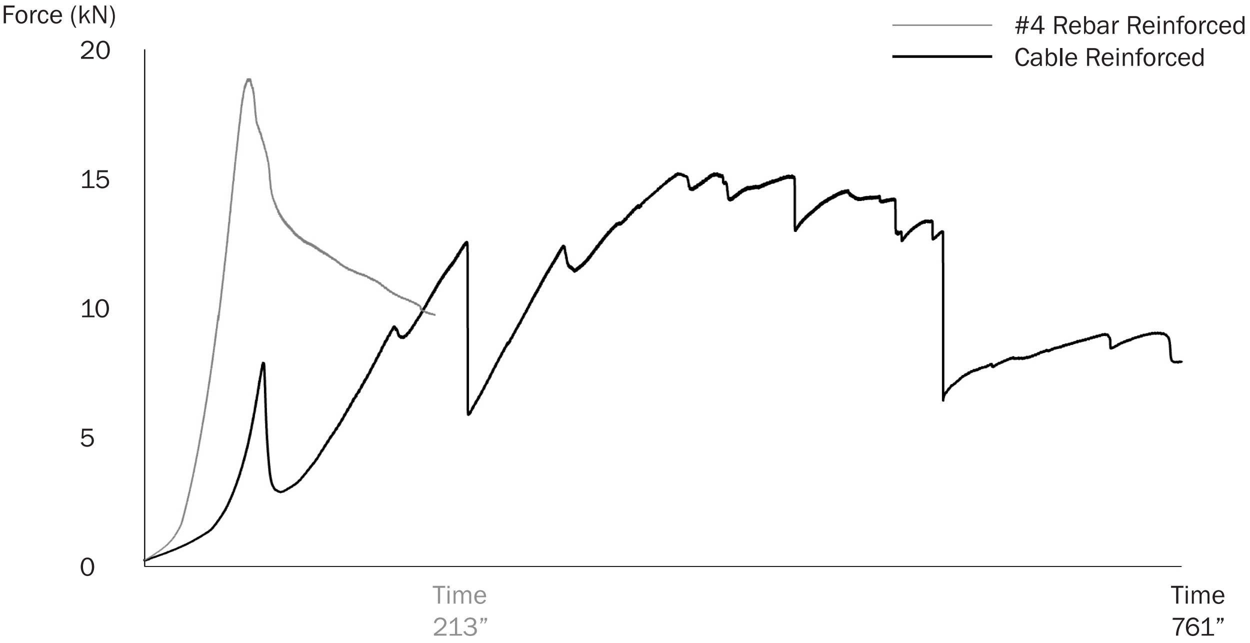


Figure 5.2.11. Three point test result.

5.3 Erosion for Demolding

In my discussion of the Dual History of Concrete, I highlighted the conventional approach to formwork fabrication in concrete construction, which is both labor and material-intensive. The cost of formwork alone constitutes over half of the resources used in concrete construction (Antony et al., 2014). To address this issue, there have been numerous attempts to simplify and improve the process, with more than 85,000 patents related to concrete formwork filed worldwide (Jipa & Dillenburger, 2022).

An interesting example of an innovative approach to concrete formwork is the system developed by Thomas Edison in 1917. Edison's system involved using a single molding operation to construct a concrete building, which simplified the complicated formwork fabrication and casting process - U.S. Patent No. 1 ,21 9,272 (Edison, 1917). The Edison Portland Cement Company did manage to construct a few houses using this system in New Jersey. However, the system required a significant upfront investment and numerous molding pieces (2,300 pieces per building), which ultimately led to its failure in the market.

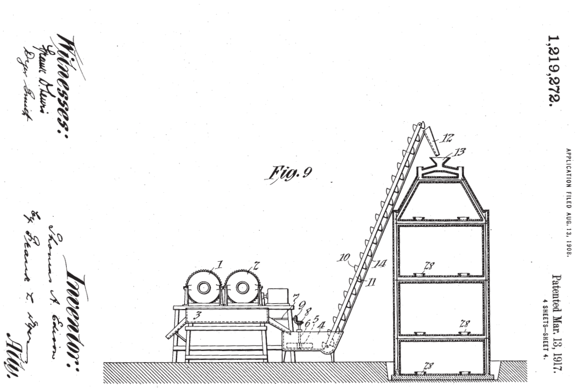


Figure 5.3.1. Process of constructing concrete buildings: Patent drawing of concrete construction in single mold operation, US1219272A, T. A. Edison, 1917.

Figure 5.3.2. Arcchitectural element from geological formation: Crowley Lake Stone Columns, Mono County, CA - Reprinted from Lorraine E. & Herbert H. Gaidus, www.cross-country-trips.com, 2018.

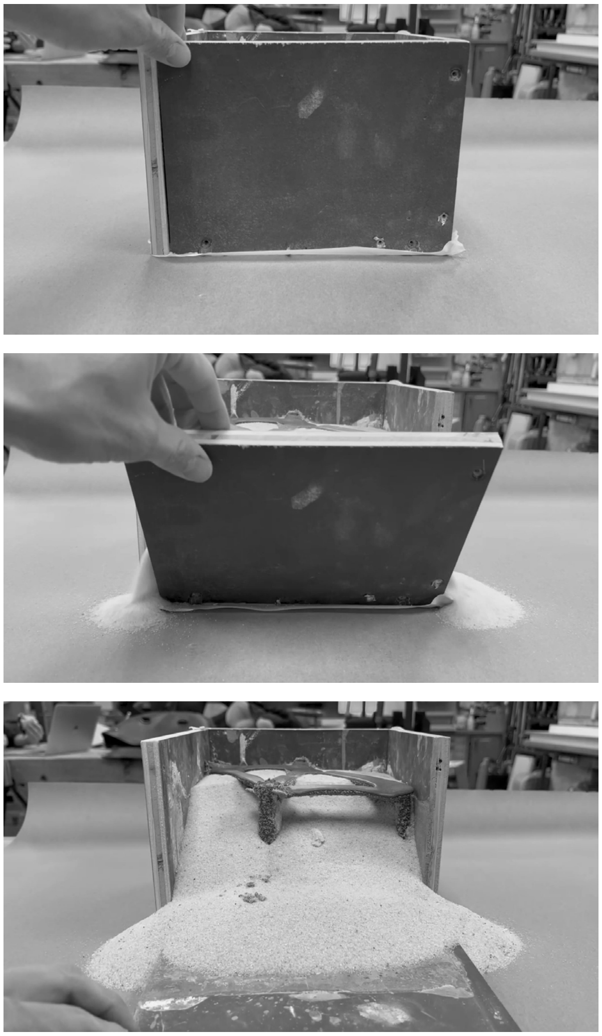
In this project, I present the geomorphic concrete design, which revisits Edison's single molding idea, but in a geological manner: The *Erosion for Demolding*. This project leverages gravity-driven mass movements, including falls, topples, slides, flows, and slope deformations, to aid in concrete construction. The fabrication process involves assembling a cage to create a sand pile, injection 3D printing concrete into the sand, and then disassembling the cage to let the sand fall naturally due to gravity. This 3D printing method utilizes sand as a medium of injection and relies on gravity in two ways. First, the weight of the sand helps to maintain the shape of the printed concrete without slumping. Second, the sand falls by gravity after construction is complete, eliminating the need for demolding numerous individual mold pieces, as was required in Edison's design. This project exemplifies the concept of utilizing gravity in concrete construction. By working with gravity instead of against it, the amount of formwork fabrication and disassembly can be less required compared to conventional concrete construction.

The erosion for demolding fabrication method produces a distinct aesthetic that showcases the process of its creation through both its surface and shape. In this methodology, the concrete is 3D printed into the sand, resulting in sand particles adhering to the concrete surface and leaving marks of their presence on the object's surface after being revealed through erosion. While the medium matter's materiality is revealed through the injection 3D printed concrete surface, this technique also produces the shape of flowing concrete. Concrete is often referred to as liquid stone, indicating its high plasticity. However, casted concrete objects from formwork only display the form of the mold and not the concrete's actual shape. So, what is the shape of concrete? A concrete structure created with injection 3D printing captures the moment of flowing concrete and freezes it in time. The printing speed, material injection rate, and concrete viscosity during printing are expressed without any constraints from the mold's shape. To clarify the process of fabrication, the following steps are involved:

1. Injection 3D Printing into Sand

Sand within formwork defines the loose boundary of the building. Concrete can be 3D printed into and onto the sand's surface by injection 3D printing method. Altering the printing speed and material feed rate can produce linear structures of different widths and shapes, even with the same nozzle size.

Figure 5.3.3. Inject 3D concrete printing into the sand: A nozzle connected to the extruder traverses through the sand and dispenses concrete. This single-stroke fabrication is inspired by Edison's invention and the geological formation process of column structures found around Crowley Lake.



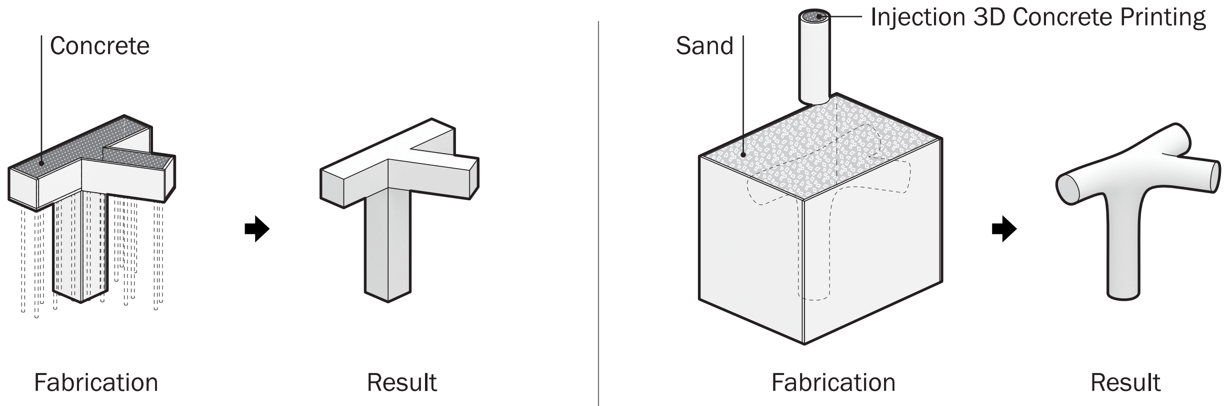
2. Formwork Removal

Removing formwork for this fabrication method is simpler than conventional construction. Only the box containing the sand needs to be removed, while the rest of the process occurs naturally. Similar to landslides and gravity erosion, the sand falls from the 3D printed concrete structure due to gravity.

3. Potential Application

This fabrication method enables the construction of concrete structures without the need for complex formwork fabrication and disassembly processes. It can be combined with other construction methods to create diverse designs. For instance, columns and beams can be injection 3D printed, and a slab can be cast on top of the printed structure. Furthermore, the sandbox can be extended vertically, akin to slip-casting, to fabricate taller structures.

Figure 5.3.4. A sequence of gravity demolding: Once the sandbox is taken apart, the sand falls from the concrete structure due to the force of gravity.



Conventional Formwork

- Delicate formwork
- Labor intensive construction
- Complicated demolding process

Erosion for Demolding

- Require less formwork
- Automated construction process
- Require less labor, faster demolding process
- Molding medium(Sand) can be reused

Figure 5.3.5. Advantages of erosion for demolding: Key differences and advantages of Erosion for Demolding method compared to the conventional concrete construction.

Figure 5.3.6. Edison's column: A concrete column constructed with conventional formwork - Reprinted from Thomas Edison NHP, npgallery.nps.gov, 1915.

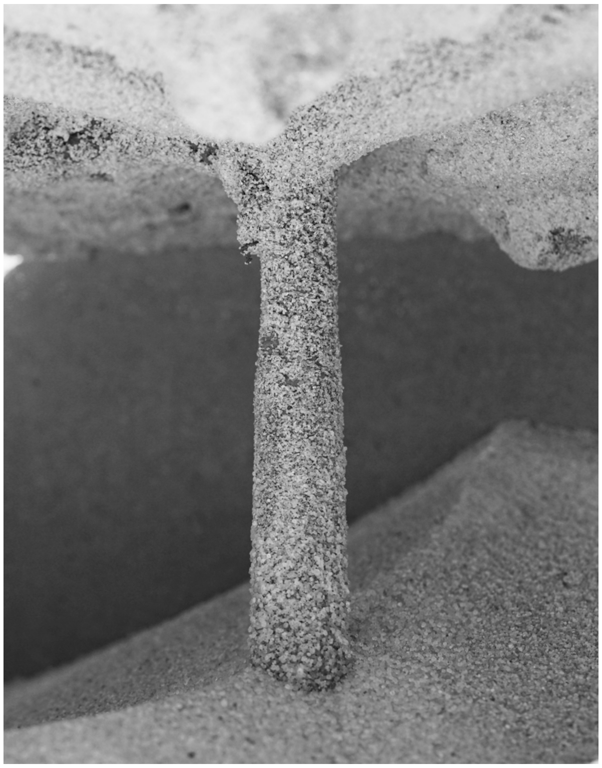


Figure 5.3.7. Geomorphic concrete column: A concrete column fabricated through gravity demolding process.

Figure 5.3.8. Erosion for demolding model with slab and stalactites.

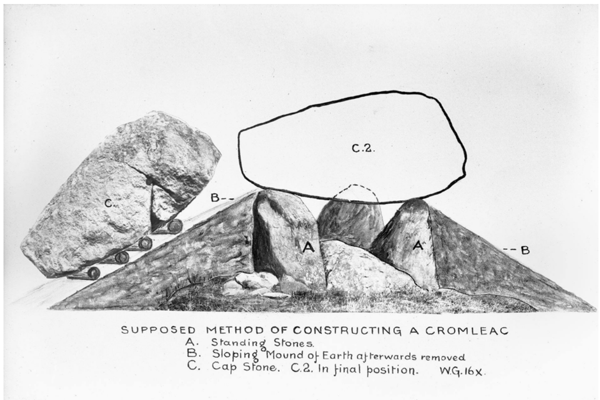


Figure 5.3.9. Dolmen Construction: Diagram of how dolmen is constructed - Reprinted from: William Alfred Green, carrowkeel.com, early 1900s.

Figure 5.3.10. Geomorphic dolmen: The slab was positioned on top of injection 3D printed columns using a dolmen construction technique.

Figure 5.3.11. Geomorphic concrete frame structure: Close-up picture of a concrete structure fabricated from injection 3D concrete printing into sand.

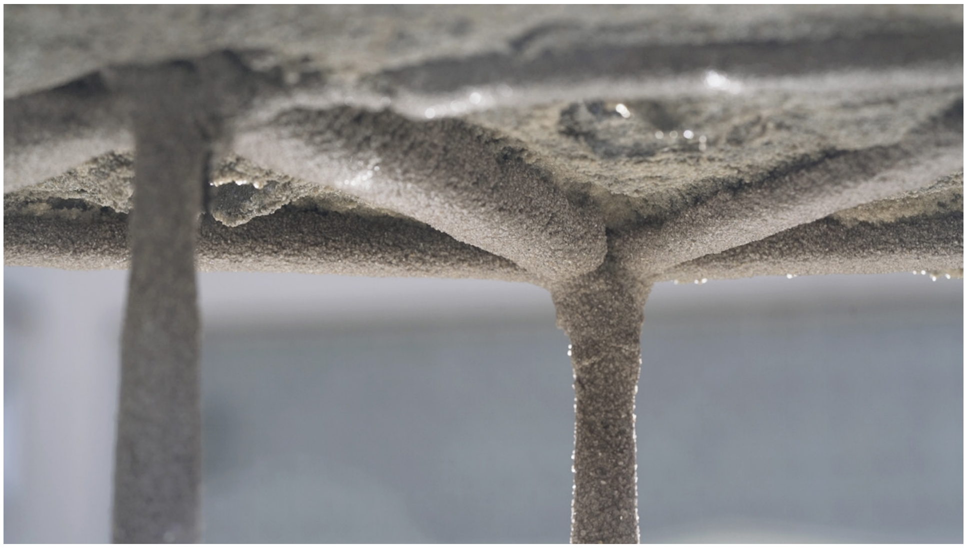


Figure 5.3.12. Geomorphic concrete frame structure and slab.

Figure 5.3.13. Geomorphic concrete tall structure: By stacking sandboxes based on the extending injection printing height, it is possible to construct taller structures.

Figure 5.3.14. Architecture from nature-1: A photo collage featuring model images illustrates an alternative architectural vision that incorporates gravity in the construction process. Inspired by the formation of caves and standing rocks through the natural forces of water, wind, and gravity, this system proposes erecting architectural structures using similar principles. The resulting fabrication process and aesthetic expression are close to nature.

Figure 5.3.15. Architecture from nature-2: The geomorphic structure adapts and evolves to changing climates and environments. This image represents the skylight that is created by rain.

Figure 5.3.16. Erosion for Demolding for tall structure - 1

Figure 5.3.17. Erosion for Demolding for tall structure - 2

5.4 Dissolution for Forming

Karst caves are naturally formed over geological time scales through the dissolution of limestone, as weak acid water slowly melts calcium carbonate and creates cavities within the land mass. However, can we replicate this process and create human-made structures that adapt natural forces into formation process and evolve with time? My research into mineral solubility has provided a solution.

By comparing the solubility of calcium carbonate (0.0015 g/L) and sodium chloride (360 g/L), it becomes clear that limestone (calcium carbonate) dissolves 240,000 times slower than salt (sodium chloride). By using a mineral with a solubility between these two values, it is possible to create an object that slowly transforms over time, similar to the formation of a karst cave, but on an architectural time scale.

After researching different minerals, I have discovered that gypsum has a solubility of 2.531 g/L, making it an ideal material for this purpose. Moreover, by mixing gypsum with portland cement, I could adjust the solubility and durability of the material. The more cement to gypsum ratio, the less soluble and more durable the mixture becomes. By 3D printing the gypsum mixture into the liquid concrete, the casted object is exposed to water and slowly reveals the concrete part as the printed gypsum erodes.

The dissolution for forming technique differs from conventional manufacturing methods as the object evolves to its designed shape at its own pace, creating a constantly unique object. Slow forming concrete, a product of dissolution for forming fabrication, can be used at different scales, from architecture to infrastructure. For example, it can be used for coastline reconstruction, where structures slowly shape and adapt to the waves and surrounding landscape. In architectural scale, structure components that evolve over time and become more efficient and optimized. Not only for the technical improvement of architectural components, This method can be also used for architectural design purpose. Imagine a building like Rudolph Hall in Yale University, where the facade forms itself over time instead of being chipped by hammers, fulfilling Paul Rudolph's design vision in a long time frame. Other applications of this technique include:

Figure 5.4.1. Crafting surface: Construction worker hammering façade of Yale art and architecture building designed by Paul Rudolph - Reprinted from dirtymodernscoundrel.blogspot.com, 1963.

Figure 5.4.2. Emerging pattern: sandstone of the Moenkopi Formation, Capitol Reef National Park, UT, Daniel Mayer - Reprinted from en.wikipedia.org/wiki/Bedform, 2005.

1. Wall

Høyblokka, a monumental brutalist government building in Oslo, was renowned for its murals by Pablo Picasso and Carl Nesjar. These murals adorned both the exterior and interior walls of the building and were created by sketching the design onto large concrete surfaces before sandblasting along the sketch lines. The sandblasting process revealed the aggregates within the concrete, creating a striking contrast between the etched lines and the smooth background wall by casting shadows on the rough lines and surfaces.

What if there was a way to create images or patterns that could emerge over time without the need for sandblasting? That is where the dissolution for forming technique comes in. By using a gypsum mixture that erodes over time, I've been able to create patterns that are both robotic-controlled and hand drawn on the surface of the concrete. This method adds an extra dimension to a wall - the element of time. Unlike sandblasting, the final image is not always set in stone. Instead, it can evolve and change over time, just as aging affects the human skin. Concrete's material-embedded information for aging allows the wall's materiality to animate the building's aging process.

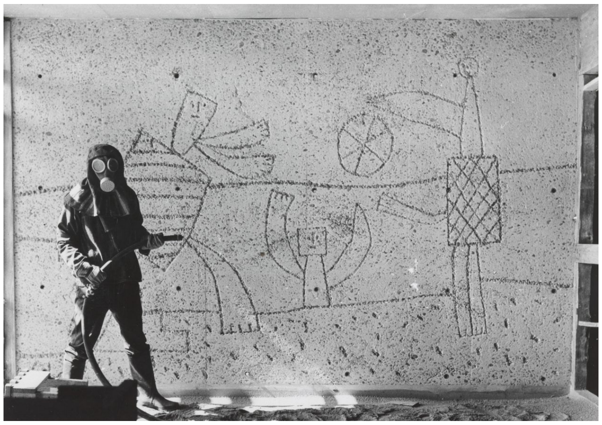


Figure 5.4.3. Sandblasted mural: Carl Nesjar sandblasting Picasso's The Beach onto the walls of Høyblokka - Reprinted from kunstkritikk.com, 1959.

Figure 5.4.4. Evolving panel: Before erosion (Left), and after erosion (Right).

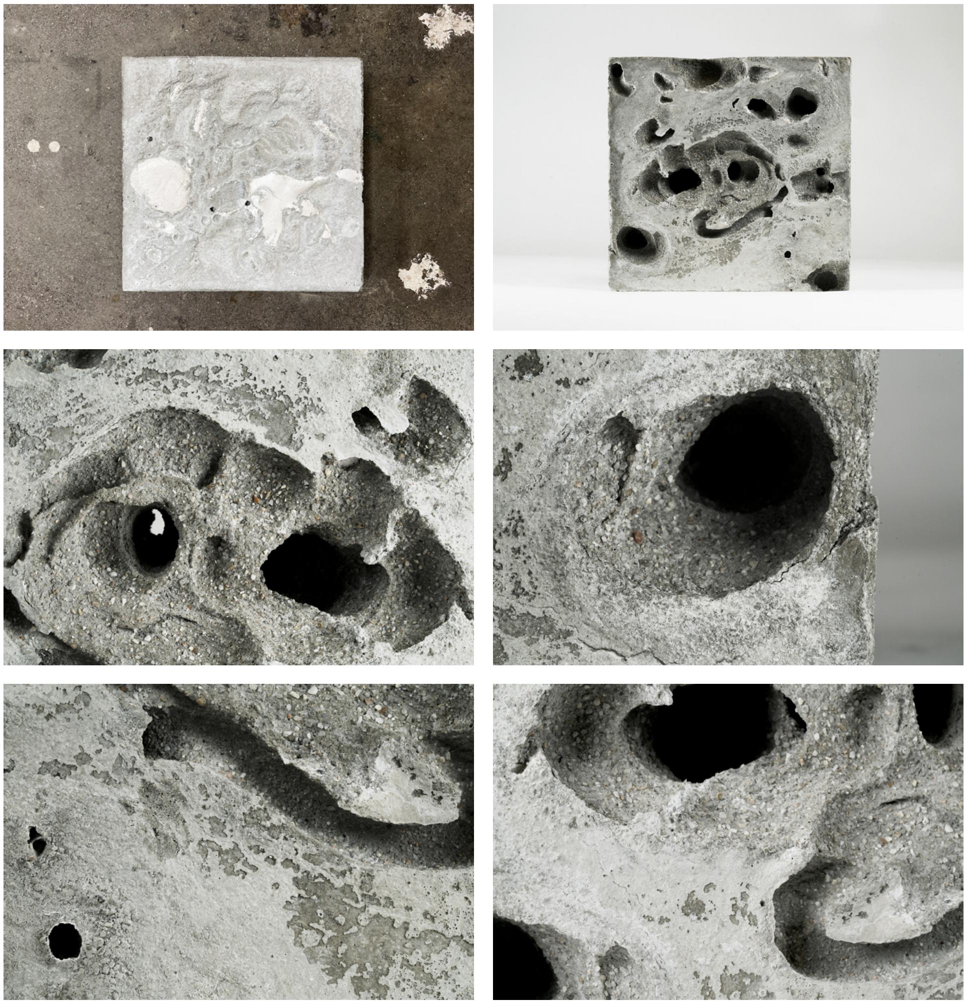


Figure 5.4.5. Evolving mass: Before erosion (Top-Left), and after erosion (Top-Right). The presence of suspension material has left cave-like voids within the concrete mass.

Figure 5.4.6. Hand extruded evolving panel: I utilized the extruder as a brush to create lines and patterns on both the surface and within the concrete panel, in a similar manner to how Carl Nesjar sandblasted the concrete wall of Høyblokka.

2. Column

Wolff’s law states that the density of an animal’s bone structure adapts to the load placed upon it, demonstrating nature’s efficiency in structural design. Similarly, architecture structures can be optimized for efficiency through generative design (Otto et al., 1990). However, as previously discussed in Chapter 5.2, topology optimized concrete structures are often viewed as less cost-effective due to the complexity and expense of fabrication. The use of dissolution in the fabrication process can simplify the production of intricate topology optimized designs. For instance, columns with complex voids can be created without the need for additional formwork. This technique can also be applied to the surface of the column to express its transformation.

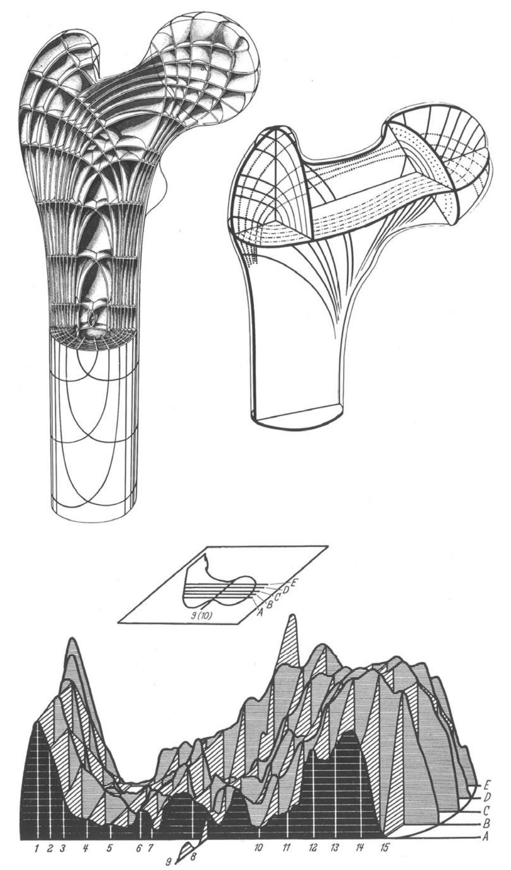


Figure 5.4.7. Bone structure: The distribution of calcium in an animal’s bones follows the path of the applied load - Reprinted from Otto et al., 1990.

Figure 5.4.8. Bone structure concrete column: Learning from the logic of bone structure,, it is possible to create more efficient structures using geomorphic concrete. This can be demonstrated through section cuts of cylinder structures with varying levels of porosity. From the top: High, mid, and low porosity.

Figure 5.4.9. Locally eroded geomorphic concrete column: By locally injecting a gypsum mixture, it is possible to create shapes and patterns that resembles the structure of a cave on a cylindrical surface.

3. Object

Objects are typically created with a particular purpose in mind and strict instructions on how to use them. However, with the technique of geomorphic concrete fabrication, objects can now evolve over time. I have designed objects that not only serve a specific function, but also possess flexibility, allowing for potential undiscovered uses in the future.

One of my designs is a concrete disc that features multiple cavities with various voids for different purposes. Three of these holes are intended to accommodate thin wood dowels for use as legs, making the disc function as a side table. Alternatively, the disc also has three larger holes designed to hold thicker dowels, allowing it to serve as a stool.

The disc also includes additional undefined holes, which are intended to emerge at a later time. These holes invite other agents to participate in the story of the object and potentially discover new and unexpected uses for the object.

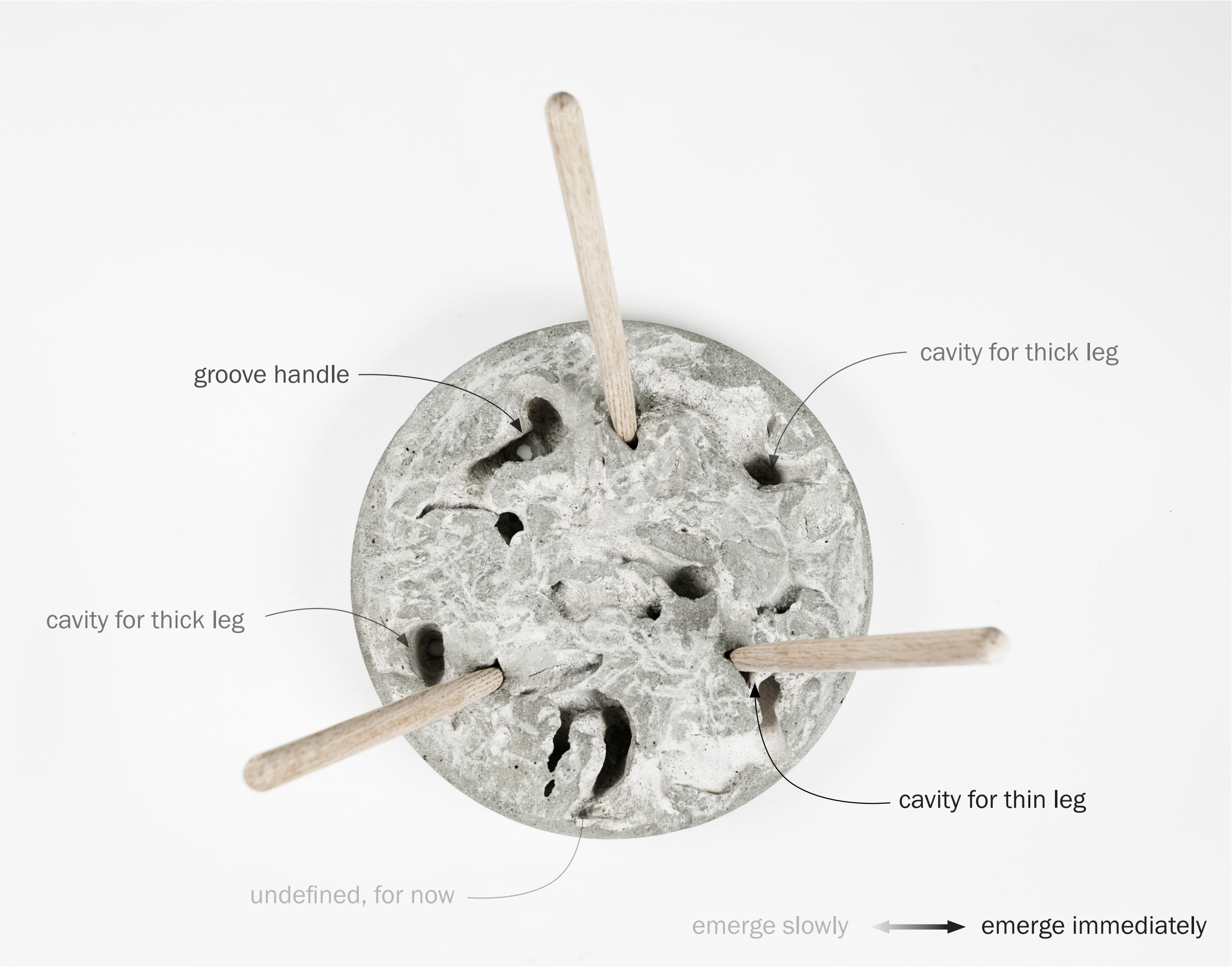


Figure 5.4.10. Evolving stool - Bottom: Numerous cavities and grooves have formed at various times, each providing unique opportunities for utilization.

Figure 5.4.11. Evolving stool - Top.

Figure 5.4.12. Evolving stool - close-up photos.

Figure 5.4.13. Ring plant: The test cylinder used to create a cylindrical crust has become the habitat of a chia plant. Its odd shapes, holes, and grooves increase the potential to incorporate additional design elements as it evolves and ages.

4. Space

In 2016, Christian Kerez designed Switzerland's pavilion for the Venice Architecture Biennale. The pavilion was a white gypsum structure resembling a cloud from the outside, with a cavernous interior for visitors to explore. Kerez named this experimental design "Incidental Space," explaining that it represented a specific event that was not predictable or calculable, yet not completely random (ARCH+ 51, 2016). The aim of this experiment was to find formal expressions that resulted from natural phenomena, such as chemical reactions, erosions, and destructions, rather than geometries designed by drafting tools.

Another architect who saw architecture as a consequence of natural events was Antoni Gaudí. His study of the catenary curve, which he called "stereostatic" hanging models, was an experiment to find a structure resulting from the natural forming process. In addition to the structural principles of creating nature, he was also interested in the formal expression created by nature. He was deeply inspired by eroded rocks, not simply by their shape but by the forming process of the eroded rock that was the consequence of natural forces. This Univers geològic (geological universe) helped Gaudí find his unique design methodology away from modernism (Prévost & Descharnes, 1969). Even before Gaudí, architects such as Jacques-Jean Thévenin and Claude-Nicolas Ledoux designed nature-looking ornaments in the 18th century France. For instance, both Grotto of the Laiterie de la Reine at the Château de Rambouillet, designed by Thévenin (Figure 5.4.17.), and Saline Royale, designed by Ledoux, have rough stone ornaments that imitate a form of natural rock.

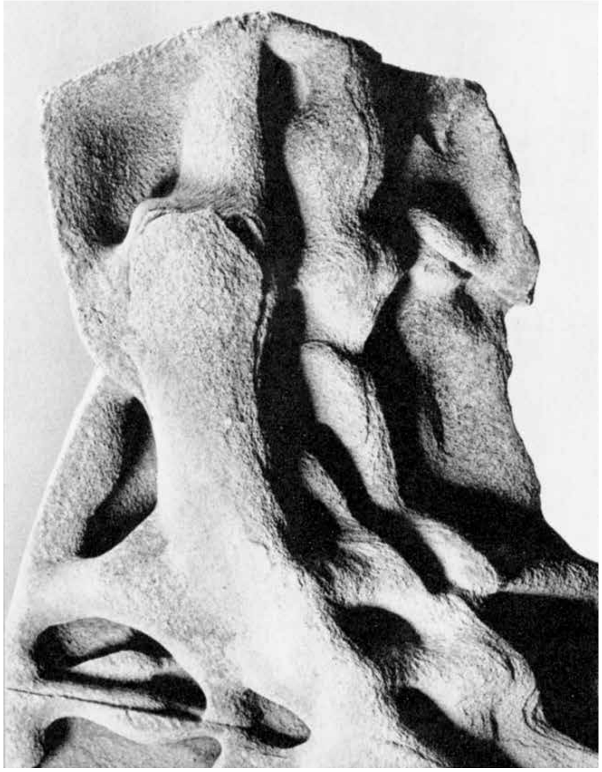


Figure 5.4.14. Eroded rock: Eroded rock from Cap de Creus in northern Catalonia - Reprinted from Prévost & Descharnes, 1969.

Figure 5.4.15. Gaudí's concrete: Eroded rocks inspired for the material and aesthetics of concrete used by Gaudí in La Sagrada Familia- Reprinted from Prévost & Descharnes, 1969.

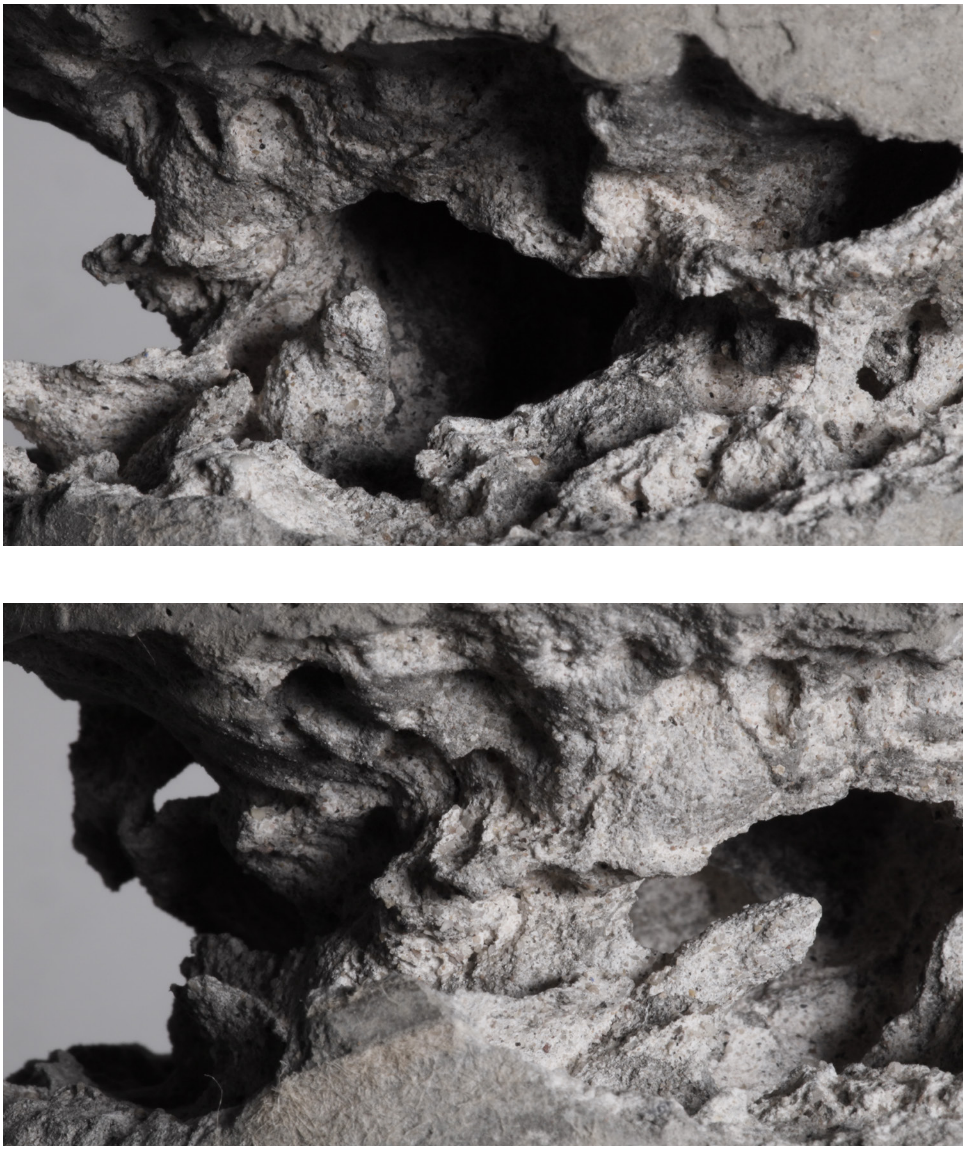


Figure 5.4.16. Geomorphic space-1

Kerez's Swiss pavilion, Gaudí's rock-inspired ornamentation, and Ledoux and Thévenin's nature-looking ornaments are underlying Gottfried Semper's theory of Stoffwechsel (Metabolism or material metamorphosis) and Marc-Antoine Laugier's description of the Primitive Hut. The fundamental idea of both theories describes how the observation of nature leads to human creation. The original structural form that is shaped from natural logic and constraint stays even after the structure is liberated from its original function and material (Moravánszky, 2018). This idea is well expressed in Laugier's An Essay on Architecture, which was originally published in 1753. He emphasizes that architecture's principles are found in simple nature, and nature's process clearly indicates its rule. By imitating the natural process, art was born (Laugier et al., 1977). However, even though nature-inspired design claims its connection to the natural formation process, the formal expression of structure has no relation to its formation process and materiality. All the examples mentioned above take logic and the appearance of nature as guidance or inspiration for design, rather than natural force as an existing agent that could build architecture with its own force.

The Geomorphic concrete method of creating space shares the same design philosophy and methodology as the aforementioned examples, as it seeks to create space as a consequence of an event. However, the project also aims to apply this concept to the fabrication process itself. While Kerez's Swiss pavilion and Gaudí's organic structures were created through experimental design processes, their construction methods did not differ significantly from other buildings. Kerez's Swiss pavilion, for example, utilized a design methodology that involved material transformation through melting, solidifying, and eroding for shape design, but this was not reflected in the fabrication process, which instead used manual labor to patch plaster on the CNC-milled frame. In contrast, Geomorphic concrete seeks to create a space that is incidental not only in its design, but also in its very essence, by shaping a space like a cave or a coastline with geological formation processes.

Figure 5.4.17. Grotto of the Laiterie de la Reine at the Château de Rambouillet designed by Acques-Jean Thévenin, 1785: Château de Rambouillet,Chatsam, (CC BY-SA 3.0) - Reprinted from commons.wikimedia.org/wiki/File:Ch%C3%A2teau_de_Rambouillet_-_Laiterie_de_la_Reine_salle_2-1.JPG, 2017.

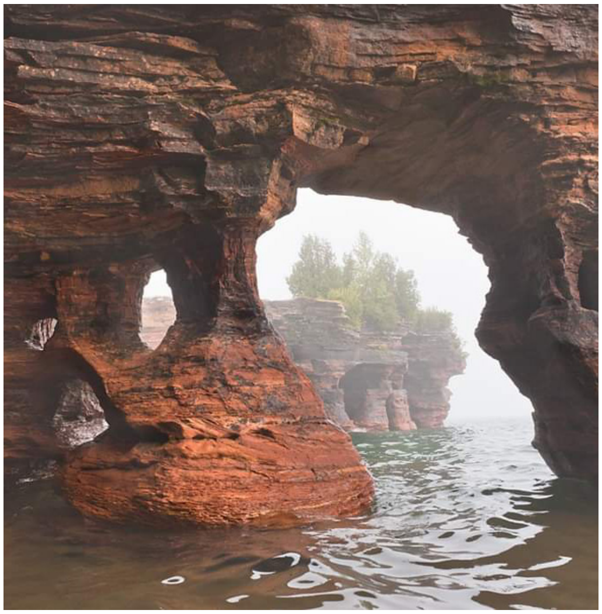


Figure 5.4.18. Apostle Islands: Labyrinthic structure of coastal line that is formed by erosion. Devils Island Seacaves, WI - Reprinted from apostleisland.com, 2021.

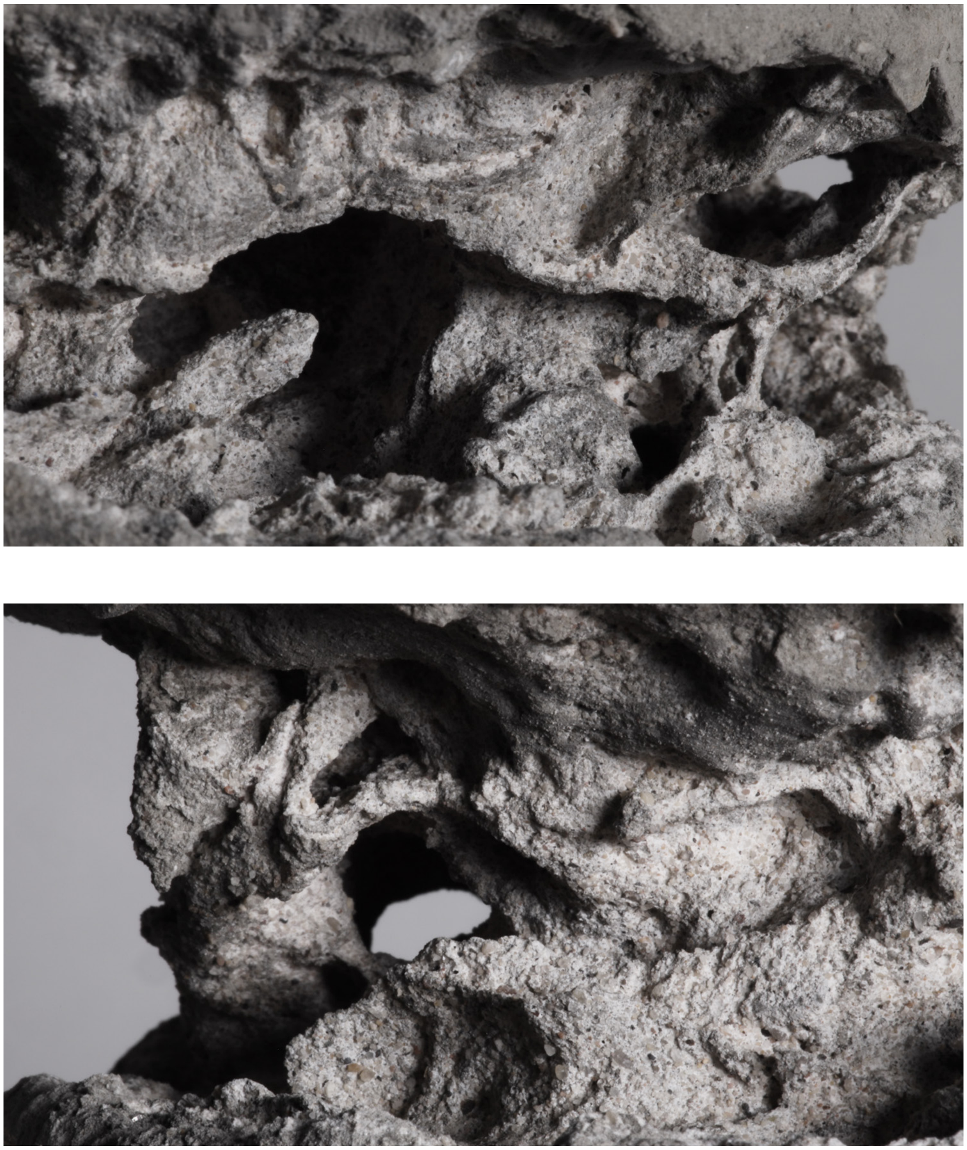


Figure 5.4.19. Geomorphic space-2

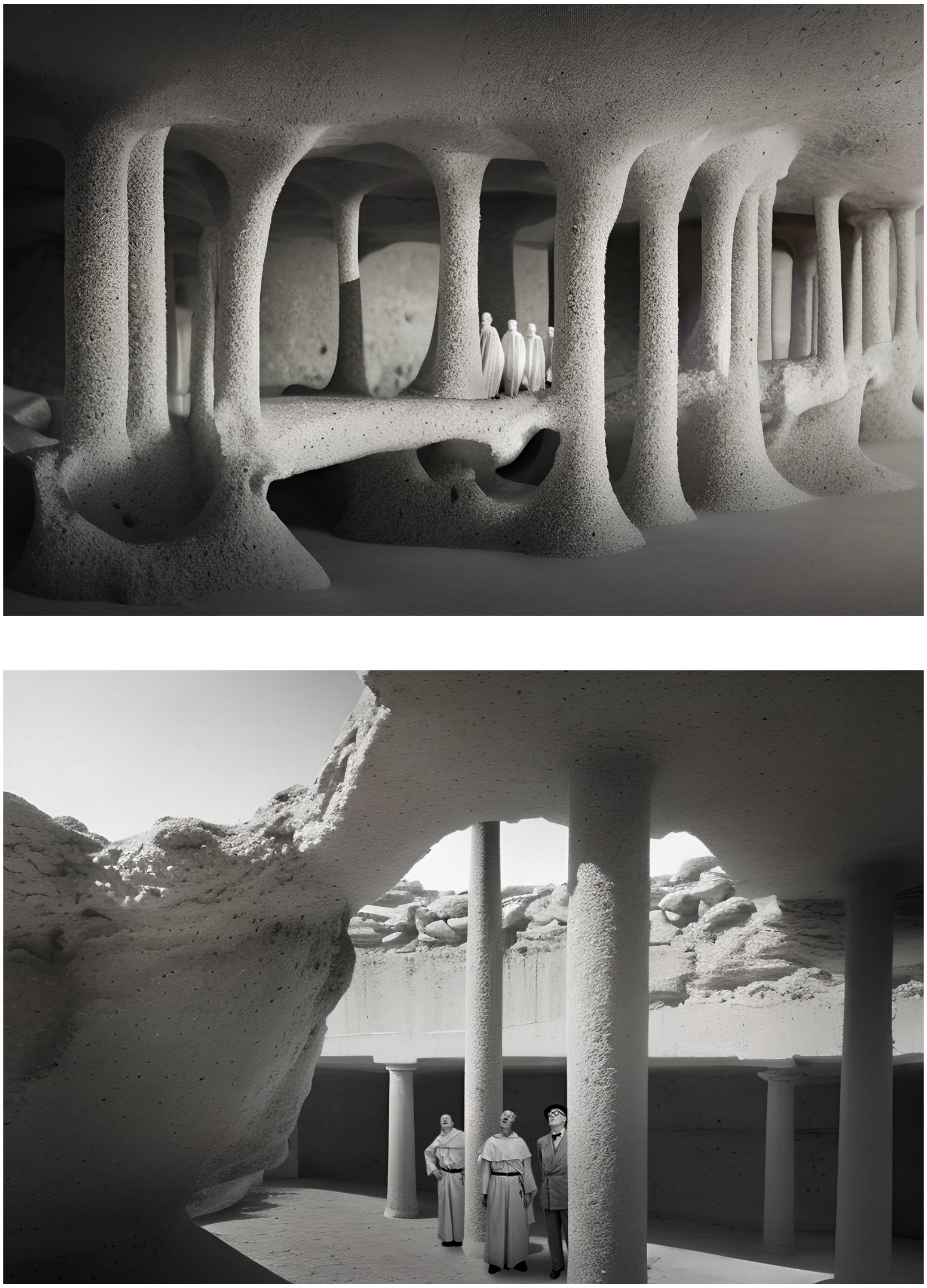


Figure 5.4.20. Geomorphic space imagination-1: These photo collages are made of AI-generated images (Runway, runwayml.com) trained by the author's model pictures.

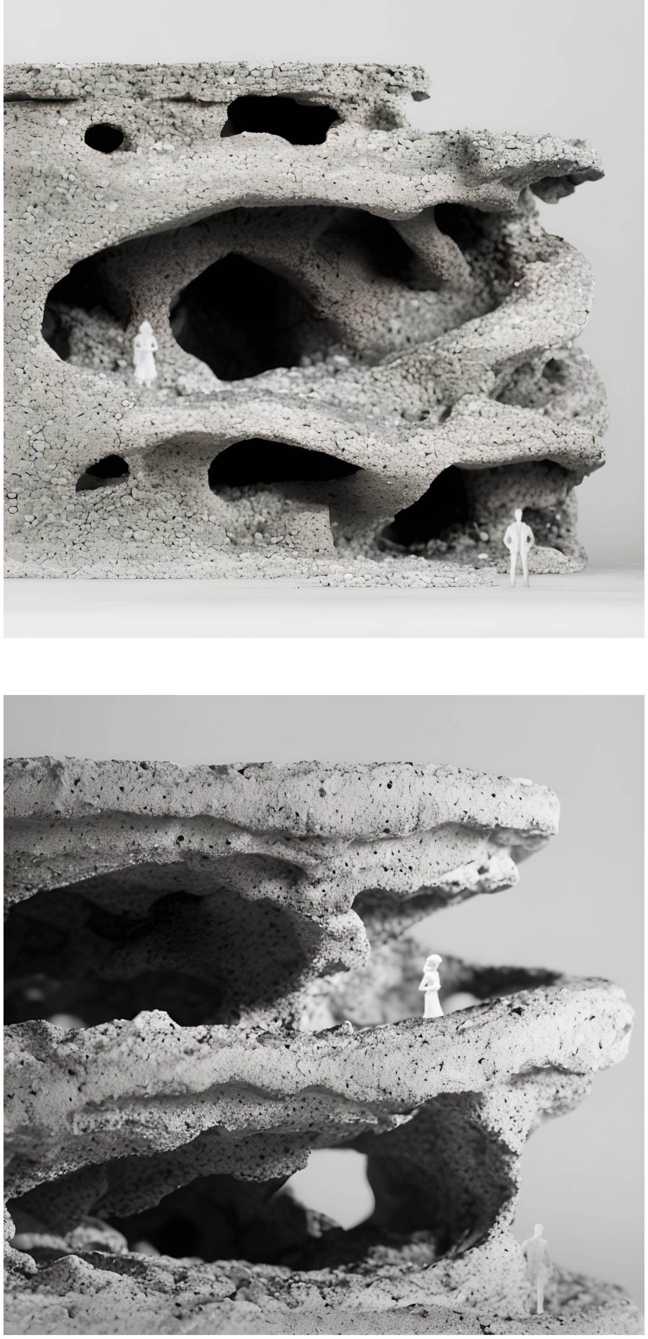


Figure 5.4.21. Geomorphic space imagination-2: These photo collages are made of AI-generated images (Runway, runwayml.com) trained by the author’s model pictures.

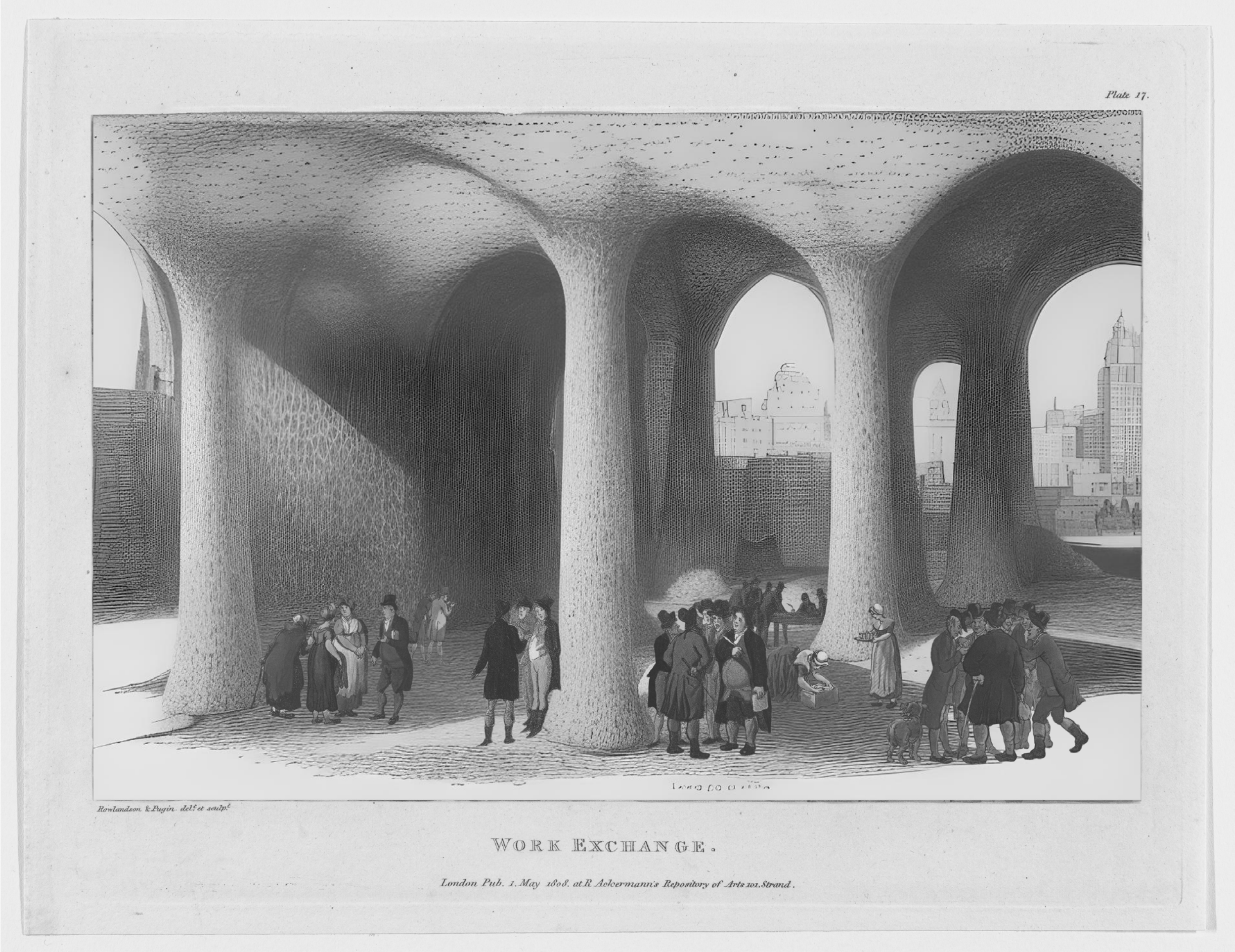


Figure 5.4.22. Geomorphic space imagination-3: These photo collages are made of AI-generated images (Runway, runwayml.com) trained by the author's model pictures.

6 Conclusion

Summary and Contribution
Geomorphic concrete proposes the geological formation process as an architectural construction method, instead of the geometry-driven design that currently dominates architectural practice. geometry-driven design approach requires excessive consumption of material and labor for unachievable tolerance in construction and ideal geometry. Alternatively, the fabrication of geomorphic concrete involves creating a concrete condition that resembles a natural geological formation and has the potential to evolve with natural forces such as erosion and dissolution. This process reveals a shape that represents a specific material condition and event that was not predictable or calculable, yet not completely random.

The use of geomorphic concrete allows for the involvement of various agents in the formation process, including technology, natural forces, material properties, and time. It does not chase after geometric goals in construction, nor blindly accept the result of the natural formation process. This thesis proposes giving up the obsession with precision in architectural construction. However, at the same time, it develops a method of achieving control in concrete fabrication by designing the material itself. For example, topology-optimized structure design is touted as a method that enables the creation of more efficient structures, which could reduce the carbon footprint in construction by saving materials and building lighter elements. However, continued reliance on geometry-driven design and fabrication results in more expensive and inefficient construction. This is because fabricating the complex geometries of optimized structures can consume unnecessary resources.

Geomorphic concrete stakes out a position in between an idealized technological optimization and a specific material reality. It offers guidance on how materials can be shaped but does not aim to generate precise geometry as directed by optimization. Instead, the structural elements are shaped by a transformation of heterogeneous concrete. Concrete elements with varying material properties are fabricated by inserting reinforcement and suspension materials into liquid concrete. These structures evolve through engagement with natural agents, such as gravity and rain.

The concept of geomorphic concrete extends beyond the fabrication of structural elements. By adopting the material-based design and logic of geomorphology as a way of fabrication, architecture can be considered a ‘given’ environment, rather than a ‘built’ space. The idea of architecture as a consequence of natural logic and events has a long history, with architects such as Thévenin, Ledoux, Viollet-le-Duc, Gaudi, Kerez, and many others designing spaces based on natural laws or formal expressions found in nature. While nature-inspired design claims to be connected to natural formation processes, it often lacks a relationship with materiality and formation processes. Rather than recognizing the natural force and material properties as existing agents that could build architecture with their own force, nature-inspired design often relies on geometric logic and the appearance of nature for inspiration.

In contrast, geomorphic concrete seeks to create designs that are conditional upon natural forces, in their design intent and also in their very essence, through the co-creation of of forms like caves or coastlines with geological formation processes. This alternative concept of architecture fabrication acknowledges geological formation as ecological process and embraces elemental forces and material changes as agents in the building process.

Technical Improvement in Fabrication and Future Work

- Reduces the amount of formwork necessary for concrete construction and simplifies formwork requirements for complex topology-optimized structures (Intrusion for Performance, Erosion for Demolding, Dissolution for Forming).
- Allows for the use of more coarse aggregate in concrete mix without size constraints by reinforcement components (Intrusion for Performance).
- 3D concrete printing method that is not hindered by gravity constraints (Erosion for Demolding).
- Automates the concrete construction process (Intrusion for Performance, Erosion for Demolding, Dissolution for Forming).
- Rapid and less laborious formwork removal process (Erosion for Demolding).
- Enables reuse of molding medium (sand) and formwork (Erosion for Demolding, Dissolution for Forming).
- Enables the creation of intricate voids within concrete structures (Dissolution for Forming).
- Allows for the transformation of concrete objects and control over their evolution rate (Dissolution for Forming).

The experiments detailed in this thesis are restricted to laboratory-produced small-scale objects.In order to extend this concept to larger architectural applications, several future steps are required. Firstly, the tools used for injection concrete 3D printing need to be redesigned to accommodate larger architectural projects. Additionally, the 6-axis robot utilized in this thesis may not be sufficiently robust and dependable for larger-scale construction. Therefore, the manipulator would need to be redesigned to be larger, such as a large gantry system capable of constructing building-sized structures, or a rail-mounted system on the formwork. Secondly, the material design in this thesis still raises many questions. More thorough solubility and erosion rate tests should be conducted to explore the effect of cement admixture in gypsum mixture, which could help control erosion rate and enhance strength.

Figure 6.1. Architecture as geomorphic process: My proposal is to shift the focus of architecture away from solely depending on mechanical engines and labor, and instead embrace the natural geomorphic processes of erosion, reconfiguration, and recovery of materials to shape our living structure.

List of Figures

All images and text by the author, unless otherwise stated.

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