Building with Biomaterials

by

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

Contents

Abstract

Concrete buildings account for 80% of construction and generate 50% of global waste. Cement, which makes up 13% of concrete, is responsible for 6% of all anthropogenic emissions. To reduce a building's carbon footprint, this thesis proposes developing a new building material from waste biomass that can be used for structure. It hypothesizes that structure made with bio-composite material can resisting forces through form.

Two pathways are developed simultaneously to test the hypothesis: material studies and building science. Material studies focus on finding the optimal matrix for the bio-composite, considering material sourcing, building component dimensions, shrinkage and curing time while the building science pathway focuses on digital form finding, construction techniques and workflow. This thesis proposes the building of a quarter of a funicular structural vault as its final product to demonstrate material properties, fabrication technique, construction workflow and feasibility of building with biomaterials.

Acknowledgements

I thank God for his goodness and wisdom.

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Many many thanks.

Chapter 1: Introduction

A Call to Build Responsibly

There is a call to our generation as designers to build responsibly. Raw materials are rarely found in the nature and available for immediate use without additional processing. They must be extracted, manufactured, and transported before made use in fabrication and construction of projects (Gesimondo and Portell 2011, 21). In our current economy, materials are taken from the Earth, made into products and eventually being thrown away as waste. This is a process known as the linear process. On the contrast, a circular economy that stops waste being produced in the first place provides a much more sustainable pathway. There are three basic principles in the circular economy, driven by design: eliminating waste and pollution, circulating products and materials at their highest value and regenerating nature (Ellen MacArthur Foundation n.d). We can build responsibly by design responsibly in the first place. This may include understanding the sociological and culture values of the environment in which we will build, choosing the right materials knowing their strengths and respecting their limits, and utilizing technology to optimize structure thereby eliminating construction waste. It is within this scope of material choices I intend to explore with this thesis, particularly the possibility of building with biodegradable materials.

Material Driven Design

I once read an analogy that compared the architectural training that provides little opportunity to experience what the building materials actually feels like to sitting through four or five years of lectures about how to cook a steak. I am grateful that my architectural training has not been like that. In particular, the work term experience I had at the Material Body Environment Lab (MBEL) has instilled in me a greater appreciation and respect for materials. The work itself has nothing glamorous about it. It consists of mixing dissolved gelatine with sand at various proportions to produce dimensionally stabled bricks. But it was in those humble encounters with the materials I learned the strength and weakness of the materials, and gained an understanding of their capacity and limits. Like Ingold said, “To know things you have to grow into them, and let them grow in you, so that they become a part of who you are” (Ingold 2013,1). This “who you are” will eventually manifest in the spaces we create, with the respect to the elements that make up the space.

My experience at MBEL has kindled in me a passion to pursue a material-driven design method, which is employed in this thesis. This thesis will first seek to develop a bio-based composite building material from converted agriculture and forestry waste biomass. Building on the knowledge I acquired from fabricating bio-bricks at MBEL, a matrix was developed that included binder and aggregate--a basic composition for masonry blocks. A series of tests were made to learn the material properties of the composite. Once the optimal mix design was identified, effort was turned into fabrication of the building component--a light weight composite that is relatively strong in compression than in tension. A digital form finding tool RhinoVAULT was used to find the optimal geometry form for the assembly of the building component—that is to keep the building components act in compression only. A combination of digital and physical modeling was incorporated to resolve issues such as footing, foundation, falsework and de-centering mechanism. As the final product of this thesis, a quarter of a full sized prototype was built to demonstrate the interrelationship between materials, form and construction method.

Chapter 2: The Proposal

Why not Concrete

What is Concrete

Let’s not assume everyone knows what concrete is. We can think of concrete as artificial rock. You mix sand and gravel (generally referred as aggregate) with some glue (usually called binder) at certain proportion and pour or spray or pack it into a form that you desired. The mixture sets and hardens and becomes the block, the wall or the building we build in modern times. The glue in concrete mix is Portland cement. It was invented in England 200 years ago by a man named Joseph Aspdin through trial and error by burning limestone over 1400 °C and mixed with ground clay. The result was a very strong product and now commonly used building material (King 2017, 69).

Why Concrete

Concrete is Strong

Sometimes, to argue why not to use a substance, we must start with why a substance is used. Concrete, especially when reinforced with steel, can achieve things that would be impossible with any naturally occurring material (Forty 2012, 43). It offers the possibility of hurricane and earthquake proof dwellings (Forty 2012, 14). Its dense mass gives it the capacity to absorb enormous forces, whether natural or man-made. It is good for foundations, sea defences, fortification, anywhere that calls for a monolithic inert. Concrete’s defensive property was recognized early on. French engineers used it successfully for the construction of a breakwater at the port of Algiers in the 1830s. By the latter half of the 19th century, concrete was widely used for military fortifications. After World War I and World War II, concrete has established its position in man's perception as "a medium that offers life through its protection" (Forty 2012, 169-180). For most of the 20th century, buildings made of concrete celebrated the material's exceptional rigidity. Concrete was used to create the unnaturally long spans, or the dangerously extended cantilevers (Forty 2012, 287). Today, concrete is the widely used structure for high-rise buildings.

Concrete is Pliable

Concrete is a mixture of aggregate, cement and water. It does not have any shape of its own. It takes on the shape of the formwork in which it hardens. The appearance of exposed concrete is dependent upon the quality of its formwork (Forty 2012, 34). From post and beam, to slab, to shell structure, to decorative cladding, concrete can be any form and shapes that expresses the design intention.

Concrete is Lasting

Although not eternal, concrete buildings last a long time. Since the early disagreeable ageing of concrete that concerned architects in the late 1950s, astonishingly large amount of time and energy has been invested in search for a time- and weather-resistant concrete. One strategy was to develop the use of precast concrete which allowed for greater control over the composition of the material, and made possible a denser, less porous and more perfect surface that was less prone to staining (Forty 2012, 54). A lot of the concrete buildings from the 1960s are still standing today if they survived demolition.

Concrete Building System is Mature

Concrete, in particular reinforced concrete, is well established as a building material, the building system is mature, which makes building with concrete relatively fast, especially with precast concrete. Concrete can be prefabricated into floor slabs, wall panels, or architectural wall panels (special exterior wall panels with architectural figures) in a factory and shipped to site for installation. The process is time efficient.

The Problem with Concrete

GHGs

Concrete buildings account for 80% of constructions (Block 2020). The problem with concrete is specially contributed by cement production which is a significant and readily identifiable source of carbon in the atmosphere. Cement, which constitutes about 13 percent by weight of normal concrete, generates exceptional amount of carbon dioxide in the air: for every ton of Portland cement production, one ton of carbon dioxide is generated (Forty 2012, 69). Cement production accounts for 6 % of all anthropogenic global emissions (King 2017, 69).

Natural Resource Depletion

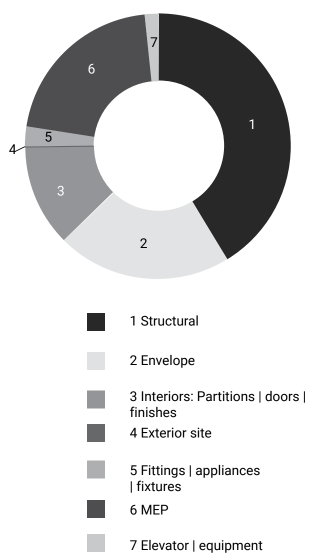
Besides generating tremendous amount of carbon dioxide, the building industry is also responsible for depleting natural resources in the world. “More than 50 percent of the natural resources used worldwide are consumed by the building industry alone” (Sobek 2010, 34). Concrete production is estimated to consume annually 8 billion tons of raw materials, mainly sand and gravel, but also limestone (Forty 2012, 69). More than 10 billion tons of concrete are currently used every year and it is estimated to reach 60 billion tons in 2050 (Block 2020). According to King, there is not enough cement-making capacity in the world to take care of construction for the 3 billion people due in the next 15 years (King 2017, 70). It is also said that sand, the fine aggregate in concrete, will no longer be economically available in the next 30 years (Block 2020).

Waste

50 percent of total waste worldwide are produced by the building industry (Sobek 2010, 34). Construction debris and demolition waste is estimated to contribute between 25 and 50 percent of all municipal solid waste in Europe (Forty 2012, 76). While some of the demolished concrete building debris can be crushed and reused as aggregates in new batches, the percentage is low. The majority of waste goes to landfill.

Embodied Carbon

The greenhouse gasses emitted in the process of extracting, producing, transporting, using and waste-treating materials, is commonly known as the carbon footprint. A building's embodied carbon is related to its materials chosen and the quantities of materials use (King 2012, 17). The diagram represents a relative contribution of initial embodied impact to the construction of a high-rise residential tower (King 2012, 20). In this building, the structure (assuming it is concrete, as the most used structural material for residential high-riser buildings) is about one third of the total impacts.



Relative contribution of initial embodied impacts (cradle-to site) to construct a high-rise tower (Redrawn from King 2017, 20)

Thesis Question

What if we can substitute this one third of imparts with carbon neutral or even carbon negative building materials,

Road map illustration

say, a bio-based composite made from recycled biomass? The benefit of this proposal is twofold: it creates an avenue through which waste biomass generated by agriculture, forestry and even food industry can be put back to the loop while help reduce the carbon footprint of the building.

The Road Map

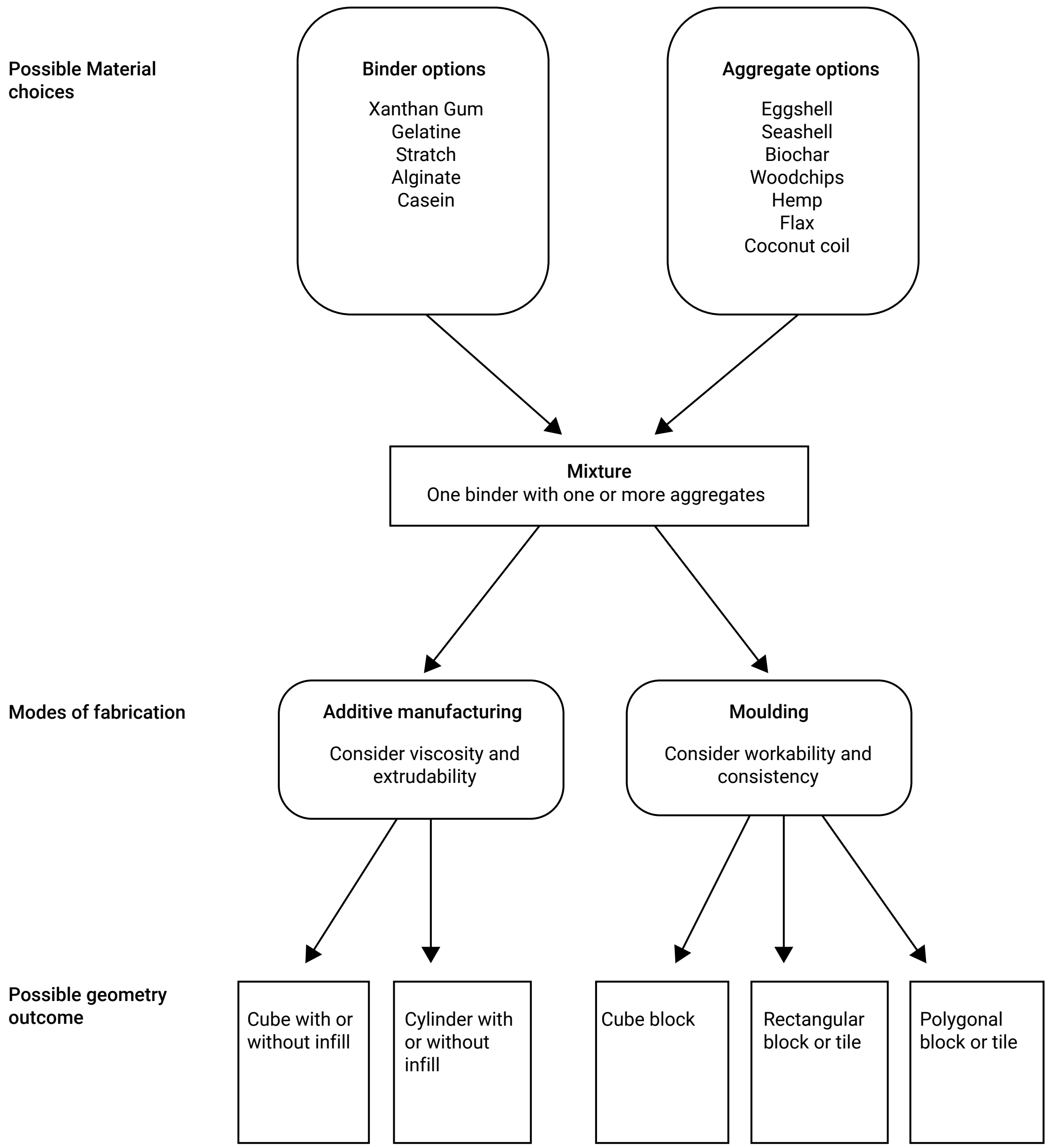
This thesis will approach this question from aspects of material studies and building science. I must attribute the ability to arrive at this approach to my time at MBEL. The hours spent in brick making with gelatine and sand gave me an understanding of how a bio-polymer functions as binder and what characteristics such as mixture consistency to look for in the brick fabrication. It also introduced me to biochar (thermally converted biomass and a carbon negative material) and developed in me a sensitivity of the property change brought by adding biochar in the matrix. Waste biomass can undergo a conversion process either physically (crushing) or thermally (converted into biochar through pyrolysis), made into bio-composite as building blocks. Building blocks can through optimized geometry become structure. At the end of life, bio-composite structure can decompose and return to nature.

Chapter 3: Material Studies

Setting Parameters

Although the ambition is to find a concrete replacement, it does not mean that I have to forsake everything about concrete. As I mentioned earlier, concrete is a mixture that uses a binder (Portland cement) to glue aggregates (gravel and sand) at various proportion. Often other additives are added into the matrix to induce desired properties. Adapting the concrete mix principle, the first parameter set for the material is that it is a composite. This will allow me to create a matrix for its composition. By adjusting the proportion of one or more elements in the matrix, I can have control over the end results.

There are many possible pathways for the material studies, each will lead to a different outcome. As shown in the Possible material study pathways diagram, these pathways include material choices for binder and aggregate, modes of fabrication and possible geometry outcome for the product. Due to the time constrain of this thesis, it is not possible to explore all the possible pathways. I have chosen the entry point to be the modes of fabrication because my familiarity with moulding as a fabrication mode. Each mode requires different properties for the mixture, therefore binder choices and aggregate choices and their proportions in the mixture will be tested on the desired properties considered for that mode.



Possible material study pathways diagram

Biocomposite Matrix Based on 3D Printing

One mode of fabrication of building blocks is additive manufacturing (commonly known as 3D printing). The first sets of material studies were built upon the premise of additive manufacturing which considers the viscosity and extrudability of the material body.

Binder: Xanthan gum

Aggregate: Eggshell, biochar, woodchip

Xanthan Gum

Xanthan gum is a microbial heteropolysaccharide produced through fermentation by a genus of bacteria Xanthomonas. At a very low concentration, Xanthan gum is able to form highly viscous solution. It is stable over a wide range of pH range and promotes the development of products whose viscosity is not changed by pH due to the addition of new ingredients (Butler 2016, 2). Xanthan gum is also thermally independent, meaning it does not set when temperature drops. It hardens as water dries out, which is a desirable characteristic for the matrix.

Eggshell

The main chemical make up of eggshell is calcium carbonate. It is abundantly present in nature as in sea shells and coral. One can say, it is one of nature's structural materials, which makes it an ideal candidate as the aggregate in the matrix. Eggshell is also easy to source, from common house whole and from local restaurant food waste.

Biochar

Any farm industry waste, forestry waste and food industry waste can be thermally converted to biochar (Atalla and

Kurt 2020, 4). The biochar used in this material study was supplied by RDA Atlantic. It is less than 1mm in size. It acts like a filler in the matrix and absorbs water from the matrix, which helps maintain the geometry stability and reduce shrinkage.

Woodchip

Woodchip is abundantly available from the school Wood Shop. Woodchip used in this matrix was first dehydrated in oven at 100 °C for 15 minutes and ground into fine powder to satisfy matrix extrudability. It was intended to help stabilize biocomposite dimension and reduce cracking during drying.

Experiment 1

Initial test was done by 3D printing the matrix through a syringe with a 5-mm nozzle. At this early stage, the mode through which the building component will be delivered is undetermined, whether by 3D printing or by mould. Taking advantage of the high viscosity of xanthan gum, this method was selected. Another advantage of 3D print is that as each layer of material is extruded, it is easy to observe whether the matrix water content is too high or not. Xanthan gum does not set like concrete which is a chemical process called hydration, it hardens through dehydration. When the water

Initial print Iteration 1 Iteration 2

Base mix: 80g 4% Xanthan gum, 100g Eggshell

Initial 3D printing of the material

content in the matrix was high, it was observed that the print body was not able to support its own weight pass 3 layers.

Biochar was added by 5ml increment to the matrix in iteration 1 and 2. As the addition of biochar increased, the matrix was able to support its own weight without collapsing inwardly at the testing height.

Experiment 2

The previous experiment showed that when the water content in the matrix is high, extruding layer has a tendency to collapse inward. In this experiment aggregate content was increased. Print was extruded by hand with a 5-mm nozzle syringe. The first print was a 3-in diameter single wall ring. Mixture appeared to have good consistency. Extrusion was smooth and the first two layers seemed to be able to support self weight. At the third layer, extrusion started to fall inward. The second print was a 3-in diameter double wall ring. The additional wall added stability to the structure. Layer height passed three until it became too difficult to maintain precision by hand. A 2-in diameter single wall print and a

3-in diameter single wall, wall collapsed inward at third layer.

3-in diameter double wall, wall supported selfweight passed the third layer.

2-in diameter single wall, wall performs slightly better but start to collapse at the end of the third layer.

2-in diameter double wall, wall well supported selfweight for 3 layers.

100ml 4% Xanthan gum, 120g Eggshell, 5ml Biochar

Second print test of the matrix

2-in diameter double wall were also tested respectively. The general observation was that the smaller the diameter, the more stable the structure was. Double wall will add stability to the structure.

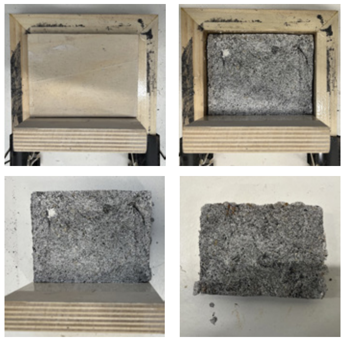
Print samples were left on the plywood base to dry in a room with temperature ranges from 16°C to 18 °C, relative humidity 55% and checked after 10 days. Some shrinkage was observed. One surprising discovery made was that the prints were well bound to the plywood base that it was impossible to remove them without breaking them.

Experiment 3

Preliminary 4in x 8in x 1in mould test

Having done two print tests with the matrix, it became clear that to make an object through 3D printing by hand will require far more practice than I had time to offer. If additive manufacturing was the chosen method to fabricate building component, It will require aide from a 3D printing machine that is also able to produce the component at the scale that I intend to work with. At the time of this investigation, such condition could not be satisfied. Attention was then turned to the method of moulding. A preliminary test was done in a 4 in x 8 in x 1 in mould. Matrix used was 500 ml 4% Xanthan gum with 200 ml eggshell and 300 ml biochar. Multiple cracks and shrinkage on all faces and edges indicated the need to increase the amount of aggregate. High water content in this matrix made de- moulding difficult and increased drying time. The sample was still soft to touch after one week.

In the subsequent test, aggregate to binder ratio was increased by 4.5 times. Instead of using 4% Xanthan gum, 9% Xanthan gum was used. Sawdust was also added to this matrix to increase stability. The mould was adjusted to 3in x 4in with a vertical board stopped by two clamps. An



Pressed 3in x 4in x 1in brick with adjusted matrix: 2 parts 9% Xanthan gum, 6 parts eggshell, 2 parts sawdust, 1 part biochar

additional face cover was also used. The brick was formed by firmly pressing the material against the perimeter and then push the brick out of mould. To help release material from mould surface, all contact surface was taped with clear scotch tape.

The brick made from the 3in x 4in mould had much better defined edges than the first one. The brick seemed to have obtained some mechanical strength after left to dry overnight. Shrinkage was not visible to human eye. This matrix is the most desirable by far for what it is intended to do.

Critical Analysis Concluding the Experiments

It was not feasible within the time constrain of this thesis to use Additive Manufacturing as a mode of fabrication as discussed earlier. Moulding showed favorable results. Xanthan Gum based matrix tends to take a long time to dry. The uneven surface and cracking results from drying can be overcome by increase aggregate proportion. The issue I might encounter with increased aggregate proportion is material sourcing and preparation time needed when scaling up, as well as the cost incurred by xanthan gum as the 3in x 4in brick contains 9 % Xanthan.

Biocomposite Matrix Based on Moulding

The shrinkage and drying problem observed in preliminary test of a 8in x 4in x 1in tile poses a concern for mass production. Scaling up makes the use of xanthan binder economically expensive. There was a need to explore a different binder. Upon consultation with Kim Thompson from the Deanery Project who is very knowledgable with natural building materials, I decided to use casein as a binder in my next material study.

Matrix with Casein Binder

Binder: casein + lime

Aggregate: eggshell, biochar, woodchip

Casein

Casein was used as glue in ancient Egypt and as a vehicle for pigments by the medieval painters. It was also widely used as glue in Germany and Switzerland in the 1800. Around 1930 it had become a recognized adhesive in aircraft and yacht work (Gordon 1968, 93). In a recent study done by Chang et al (Chang, Im, Chung, and Cho 2017), casein was used as a soil strengthening binder. It was a common practice to add bio-polymers such as blood or casein to lime mortar to improve workability and strength. Casein can be derived by adding vinegar to skimmed milk, both at room temperature and let the mixture sit for a few hours until the precipitated casein curd is separated from the whey. The curd is then washed with water to neutralize the acid and drained. The obtained casein can then be mixed with dissolved lime to make casein binder. Casein reacts with lime and forms a substance called calcium caseinate, which is a water-insoluble salt.

Lime

Lime was the traditional base for both mortars and plasters. It comes in a form of quicklime and slaked to produce lime putty used as the basic ingredient for various mortar mixes (Yeomans 1997, 46). Slaked lime is also called hydrated lime. The lime used in the matrix is hydrated lime purchased from Shaw Brick.

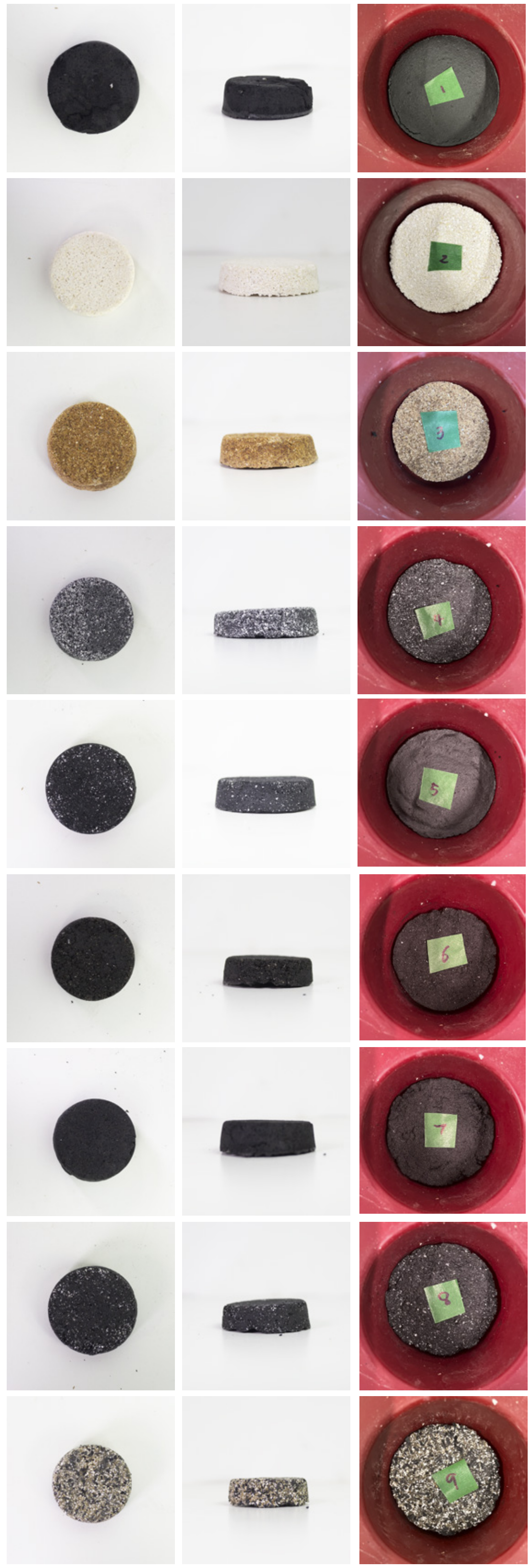
Testing for Aggregate Composition

The first set of samples test for the optimal aggregate composition in proportion to casein binder. All dry ingredients were measured by volume and prepared using the ratio recorded in the Table 1. Casein lime binder was prepared separately by adding 15 ml hydrated lime powder with equal amount of water to every 100 ml of casein. Casein lime binder was then mixed by proportion with dry aggregate. Samples #1, #2 and #3 were control samples. Each was made by mixing casein lime binder with only one aggregate, whether it be biochar, eggshell or woodchip. Other samples adjusted the proportion of these three ingredients to find the matrix with least shrinkage. After the desired mixing consistency was achieved, mixture was poured into 6-cm round silicone mould. Samples were left in mould overnight and de-moulded the following day. De-moulded samples were left in room at 20°C to dry until no more weight loss was observed. Samples were then put back to mould to observe shrinkage. Samples #5, #7, #8 and #9 were observed to have the least shrinkage.

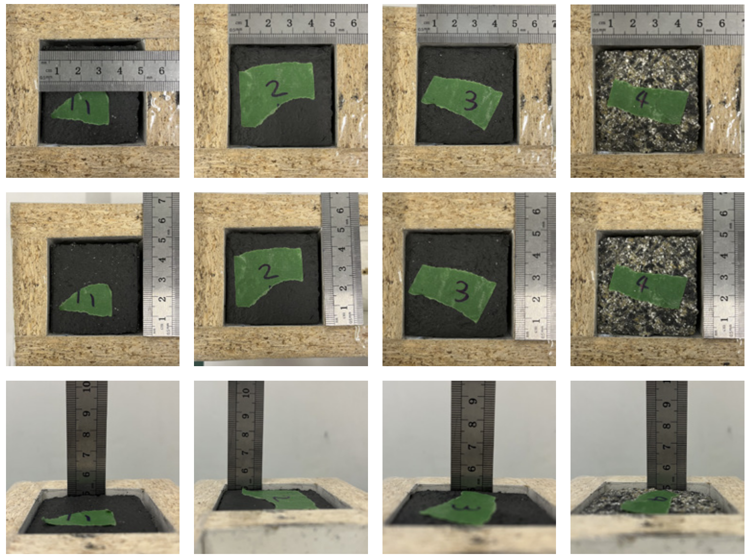
Sample #5, #7, #8 and #9 composition were then cast in 5 cm cube in a subsequent test to measure shrinkage

Index	**Binder (casein + lime)**	**Eggshell**	**Woodchip**	**Biochar**		
1	2	-	-	3		
2	1	3	-	-		
3	2	-	3	-		
4	1	2	-	1		
5	1.5	1	-	2		*
6	2	-	2	1		
7	2	-	1	2		*
8	2	1	1	1		*
9	2	1	1	1	(coarse char #7-14)	*

Table 1: Matrix ratio for 6 cm round samples



6 cm round samples, #5, #7, #8, #9 have the least shrinkage.



Samples cast in 5 cm cubes and shrinkage measured

Index	Previous	Binder (casein + lime)	Eggshell	Woodchip	Biochar	Shrinkage
1	#8	1.5	1	1	1	18.71%
2	#7	2	-	1	2	13.37%
3	#5	1.5	1	-	2	11.53%
4	#9	1	1	1	1	13.37%

Table 2: Matrix ratios for 5 cm cubes, shrinkage recorded

percentage. Observations were recorded in Table 2. Sample #5 had least amount of shrinkage, which contains 2 parts of biochar to 1 part of eggshell. Based on this observation, I made an assumption that biochar may help stabilize the sample dimension. The next question is, will this proportion work when scaling up? Although the greater percentage of biochar resulted in the least shrinkage, it reduced the sample weight substantially. wI was not certain how weight might affect the mass production phase and the building phase.

Scale-up Test

While the samples appeared to be dimensionally stable at 5 cm cubes, it was uncertain to me whether they will remain dimensionally stable with increased sizes. The outcome could be a brick or a tile. Both are with increased surface area. A tile also has decreased thickness which can

Index	Binder (casein + lime)	Eggshell	Woodchip	Biochar
1	2	-	1	2
2	1.5	1	-	2
3	1	1	1	1 (coarse char)
4	1	2	-	1
5	1.5	1	1	2

Table 3: Matrix ratio in 20cm x10cm x1.2 cm tiles

20cm x10cm x1.2cm tiles made with 5 different matrix dried at room temperature.

have tremendous impact on drying. I went with the more challenging tile. Table 3 shows the mix design to test in 20cm x10cm x1.2cm tiles.

A new challenge arose when dimension increased. The increased surface area caused the tiles to wrap when drying. A number of drying method was also explored at this phase including:

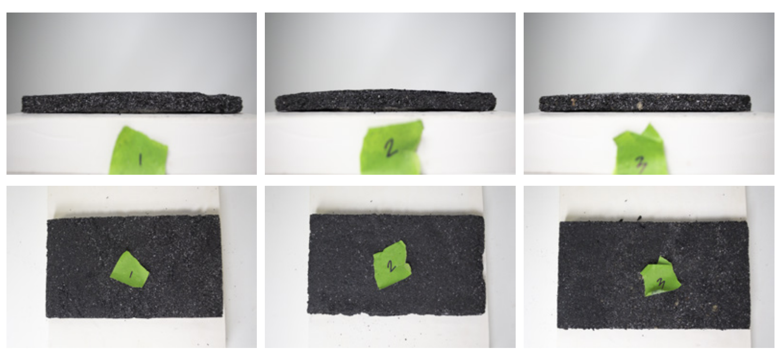
- Drying on plaster
- Drying on gypsum board
- Drying on wire rack
- Drying on plastic sheet and flip the tiles every 8 hours

Each method has its advantages and disadvantages. To sum up a few, while wire rack provides the best air circulation and most even drying, the number of racks I have access to was limited and would not be able to accommodate mass production. Casein glue is an excellent binder to wood and paper. The tile that was dried on gypsum board was bound to the paper so tight that the tile could not be removed from the drying surface without being damaged. Although drying on plastic sheet and flip the tiles every 8 hours seemed cumbersome, it seemed to be the most feasible drying method.

Sample #2 and #5 from the tile test had the best results in terms of dimension. Sample #4 is deceiving from the side view. The top view of #4 reveals that it is broken in half. It was noticed that both sample #2 and #5 have two parts of biochar to 1 part of eggshell. To confirm my assumption that both biochar and eggshell help stabilize dimensions. A second set of samples were made to test the effect of biochar ratio on dimension (Matrix shown in Table 4). It was observed that biochar did help with dimension, so did eggshell. I concluded that either biochar or eggshell will result in relative stable tile dimensions. The choice of which will depend on source material availability.

Index	Binder (casein + lime)	Eggshell	Woodchip	Biochar
1	1.5	1	-	2
2	1.5	0.5	0.5	2
3	1.5	1	1	1

Table 4: Matrix ratio of biochar in effect of dimension



Samples testing for biochar ratio’s effect on dimension

On the Thought of Casein

All material studies had a projection towards feasibility for mass production. When a rough calculation was done based on production of 150 20 x 10cm tiles, the amount of casein required was about 19 gallons of milk (Shown in Table 5). Attention was then turned to a series of test to reduce casein percentage that would still yield desirable results. Four samples were cast in 5 cm cubes and made with casein to lime ratio at 0.22, 0.33, 0.67 and 1, respectively (Table 6). It was observed that sample with 0.33 casein to lime ratio exhibited the least amount of shrinkage. A second

1 Tile volume (ml)	**Eggshell (ml)**	**Biochar (ml)**	**Casein Binder (ml)**	**Casein (ml)**	**Casein yield/gallon milk (ml)**
240	80	160	120	100	800
150 Tiles Volume (ml)					**# of gallon milk needed**
36000	12000	24000	18000	15000	**18.75**
	Eggshell (kg)				
	12				
Eggshell/egg (g)	**# of eggs**				
8	1500				

Table 5: Casein from 19 gallons of milk

Shrinkage for different casein content

Index	**Lime**	**Water**	**Casein**	**Eggshell**	**Biochar**	**Woodchip**
1	1	1	0.22	1	1	1
2	1	1	0.33	1	1	1
3	1	1	0.67	1	1	1
4	1	1	1.00	1	1	1

Table 6: Shrinkage test for different percentage of casein content

1 Tile volume (ml)	**Eggshell (ml)**	**Biochar (ml)**	**Lime (ml)**	**Casein (ml)**	**Casein yield/gallon milk (ml)**
240	80	160	80	26.4	800
150 Tiles Volume (ml)					**# of gallon milk needed**
36000	12000	24000	12000	3960	**4.95**
	Eggshell (kg)				
	12				
Eggshell/egg (g)	**# of eggs**				
8	1500				

Table 7: Casein from 5 gallons of milk

calculation for a production of 150 tiles using 0.33 casein to lime ratio showed a reduction in milk needed to 5 gallons (Shown in Table 7).

Final Prototype Matrix

From both Table 5 and Table 7, the amount of ground eggshell needed at 1 to 2 eggshell to biochar ratio for 200 tiles would be 12 L. From the experience of making samples for these material studies, eggshell preparation was a labor intensive process that included washing, drying, then finally grinding them into powder. Although increasing eggshell proportion will also produce dimensionally stable tiles, making more than 12 L of ground eggshells within the thesis time frame was not feasible.

Therefore it was concluded from the material studies that the matrix used for mass production will follow the ratio shown in Table 8. Because the casein will be made from fresh milk. Casein water content varies from batch to batch. Woodchip is used to adjust batch water content and the desired consistency of the mixture.

Lime	Water	Casein	Eggshell	Biochar	Woodchip
1	1	0.375	1	2	0.5-0.75

Table 8: Final prototype matrix

Chapter 4: Building Method

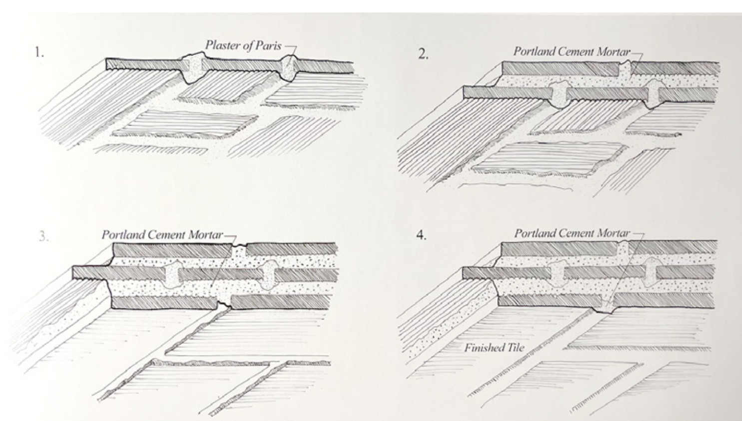
Case Study 1: Guastavino Tile Vaulting

Nothing exists in a vacuum. While researching for a suitable building method, I came across the Guastavino tile vaulting. It is also known as Catalan vaulting, a building technique widely used in Catalonia Spain. Spanish architect, engineering and builder Rafael Guastavino immigrated to the United States in the late 19th century and started the Guastavino Company. From 1881 to 1962, the Guastavino Company built more than 1000 prominent public buildings in North America employed this technique.

Lunch counter, Grand Central Terminal, New York City, 1912 (Ochsendorf and Freeman 2010,140)

The Guastavino vaulting uses thin tiles and a fast setting mortar Plaster of Paris when building its vaults. Building only 2 to 3 tiles at a time, the fast setting mortar allows the tile to cantilever from the previous one and then become support for the next tile. Usually three layers of tiles are laid with two layers of mortar in between. It requires minimum falsework. It became a fast, strong and economic structural system. Later Guastavino Jr. improved the system by incorporating Portland cement mortar and made it stronger (Ochsendorf and Freeman 2010).

Load test on a tile arch spanning 12 feet that safely carries more than 100,000 pounds (Ochsendorf and Freeman 2010,152)



Four stages of mature Guastavino tile construction procedure (Ochsendorf and Freeman 2010,127)

Case Study 2: The Mapungubwe Project

The Mapungubwe National Park Interpretive Center is a recent project employed the Guastavino tile vaulting system, designed by Peter Rich Architects and built in 2010. It was a poverty relieve project that employed local workers for tile production and construction. The tiles are made with local soil and stabilized with only 5% of cement and hand pressed. The production of tiles took a year prior to construction. The tiles are about 1 in thick and brittle. Hold on to one end of the tile, it will break by its own weight. However, put these tiles in the right geometry as shown in image C, they are

A

B

C

D

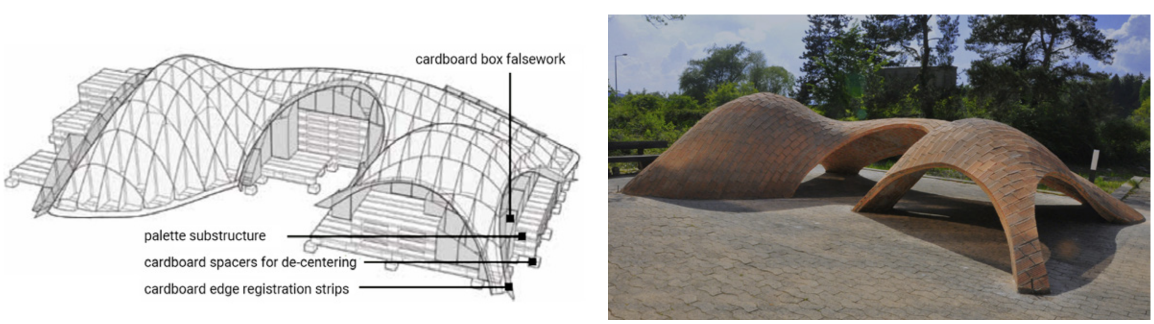
E

The Mapungubwe project photos, South Africa, 2010 (Ramage et al. 2010)
A: Project in the landscape. B: Interior. C: Worker load testing vaults. D: Guide work was built to help unskilled workers to find the right geometry. E: Hand-pressed tile with local soil.

able to support tremendous amount of load. Construction was done by unskilled local workers trained on site. Guide works were built so the workers can follow the geometry while building. The workers learned very quickly that when they followed the right geometry, the vault would stand, otherwise, it would collapse. The result was the beautiful vaulted spaces that blended in the landscape (Ramage et al. 2010).

Case Study 3: Innovative Funicular Tile Vault

The masonry construction from the old like the Guastavino tile vaulting construction technique is resurfacing in our time. One of the main forces that contributed to its revival is the Block Research Group directed by Dr. Philippe Block. This free from funicular tile vault was Block's first prototype that used modern digital tool for form finding and built using the Guastavino tile vaulting technique. The bricks in the vault were acting in compression only, which is the greatest strength of the masonry unit. Because of the complexity of the double curvature geometry, laser-cut cardboard boxes were constructed as falsework so the masons could follow



Innovative funicular tile vault, Switzerland, 2012 (Davis, Rippmann, Pawlofsky, and Block 2012) the geometry precisely. A de-centering mechanism was designed for even de-centering (Davis, Rippmann, Pawlofsky, and Block 2012).

Building with Tiles

Decision was made to fabricate tiles as the building component for building the final prototype for the following advantages: a) tiles are relative light weight compared to bricks; b) tiles has less volume which means less material is required in fabrication; c) the Guastavino tile vaulting technique that I learned from these case studies seemed to be a feasible construction method to use.

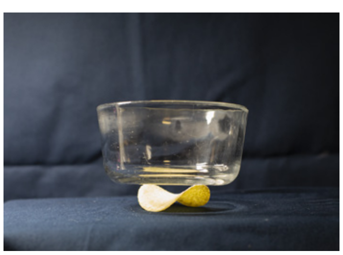
Chapter 5: Form and Structure

> The resistant virtues of the structure that we are searching for depend on their form. It is through their form that they are stable, not because of an awkward accumulation of matter. From an intellectual perspective, there is nothing more noble and elegant than resistance through form. When this is achieved, there will be nothing else that imposes aesthetic responsibility. (Anderson and Dieste 2004, 187)

Tension or Compression

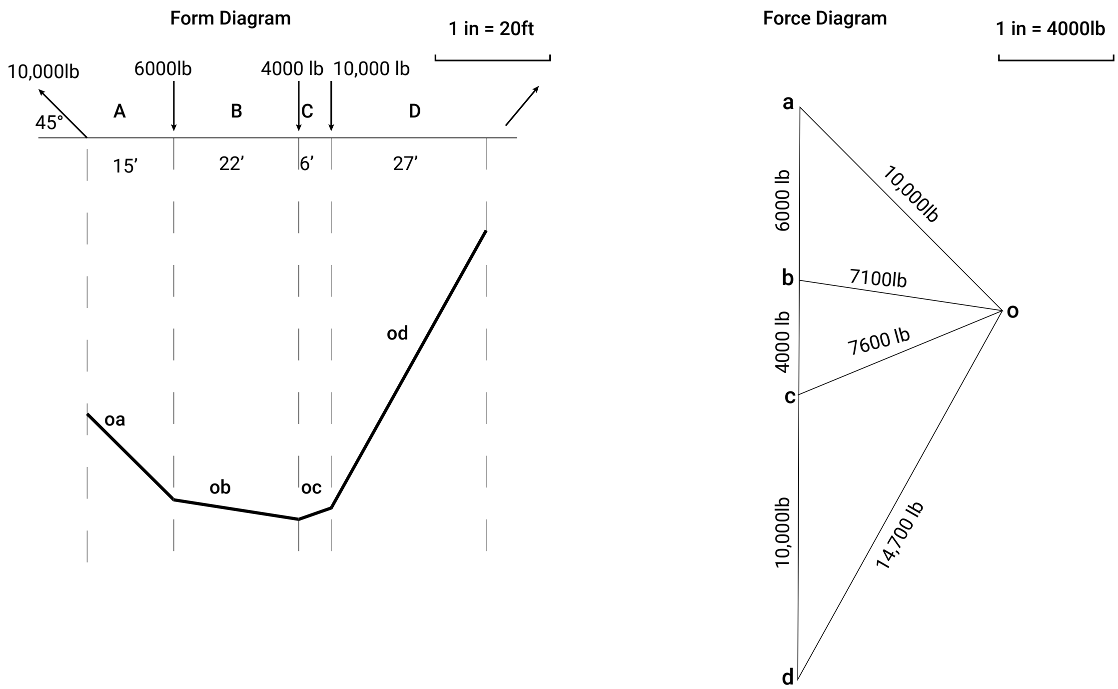
For centuries engineers and architects avoided using materials in tension as much as they could. It is not because of the lack of materials in tension (for example, wood is great for tension) but because reliable joints that can withstand tension were difficult to make (Gordon 1968, 34). The medieval master masonry builders had great success using only compression and many of the great cathedrals are still standing today. The Guastavino tile system mentioned in last chapter used compression only in construction, that is one of the reasons why the system was able to use a light weight material to build strong structures at its time.

Geometric Stability



A single Pringle chip supports 175 times of its self weight through geometric equilibrium.

The masters masonry builders knew that the stability of a masonry structure was independent of size but based on proportions (Addis 2021, 89). That is resisting forces through form. One may argue that stone is a strong material, of course it can bear a great deal of load. Such view may change when one looks upon what a single potato chip can do through form. Weak and brittle, but through the hyperbolic paraboloid geometry, one 2 gram Pringle chip can support a 350 gram glass bowl, 175 times of its self weight.



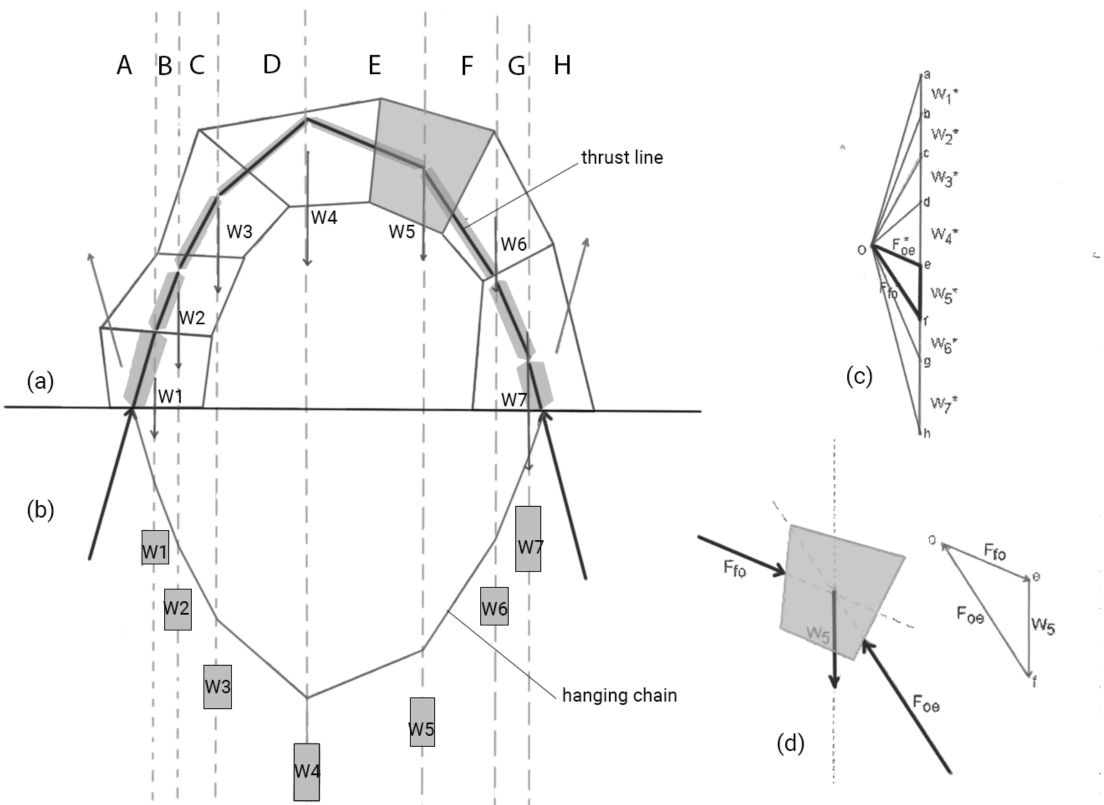
Example of graphically represented form diagram and force diagram under given load conditions. An inversion of the funicular form will act in compression only (Redrawn from Zalewski and Allen 1998,181)

Graphic Statics

The equilibrium of a structure can be calculated numerically or drawn graphically. Graphic statics is a direct way to represent form and forces happening in the form. The thick black line in the above drawing represents the form of suspension cable under the load applied. The correspondence force diagram on the right shows the stresses (tension only) in each of the segments. The form is known as a funicular polygon, referring to the form a piece of cable (or string, or rope) would assume under a given pattern of load. An inversion of the form will be a compressive structure with each member acting in compression only (Zalewski and Allen 1998, 182).

The Thrust Line

The Thrust line is an imaginary line that represents where the load is transferred in the structure. The line of thrust can be found by using either a physical hanging model or graphic statics. Either method will provide the geometry of the thrust line and the estimate of forces throughout the arch. In the random arch (shown below) held together in compression, each segment is held in place by the compressive forces applied to it by the adjacent segments. In this manner, the weight of each segment is carried down to the supports in compressive along the thrust line. Notice the inversion of the thrust

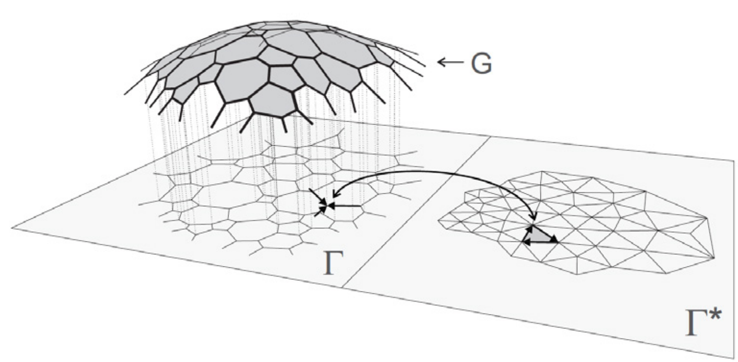


Random arch with (a) possible internal thrust line; (b) inversion of the thrust line, a hanging chain with weights proportional to the weights of the blocks; (c) the corresponding force diagram; (d) one of the arch voussoirs with a closed triangle visualizing the equilibrium of the forces that act on it. (Redrawn from Allen, Zalewski and Michel 2010, 220).

line is a hanging chain in equilibrium. The equilibrium of a single block is represented by the bold triangle shown in the funicular polygon. If the thrust line stays within the form, the structure is stable. If the thrust line is close to the boundary of the form or outside of the form, the equilibrium is broken, causing failure in structure (Allen, Zalewski and Michel 2010, 220).

Thrust Network Analysis

Graphic statics is limited to 2D drawings. There have been attempts to use graphic statics to solve complex 3D geometry, but it becomes overly complicated and difficult to read. In 2009, a MIT PHD student wrote a dissertation Thrust network Analysis to explore 3D equilibrium (Block 2009). Block used algorithm and computational design to generate the compression only equilibrium, projecting its planar form diagram and corresponding force diagram. The relationship between form diagram and force diagram is reciprocal, meaning the convergence of vectors at any given point in the form diagram will correspond to a polygon of the same number of vectors in the force diagram, or



Network relationship between the compression equilibrium structure (Block 2009, 45) vise versa. Built upon the Thrust Network Analysis, a software plug-in RhinoVAULT was created that made design complex geometry in equilibrium much easier.

Compression Only

It has become clear to me that the structure I will build with the biocomposite I fabricate will be in compression only. Here are some of the reasons: a) the literature review has supported this decision; b) RhinoVAULT that I have chosen as the digital form finding tool is mainly used for compression only forms; c) the observations I made from the material studies suggested that the biocomposite can better resist compression than tension.

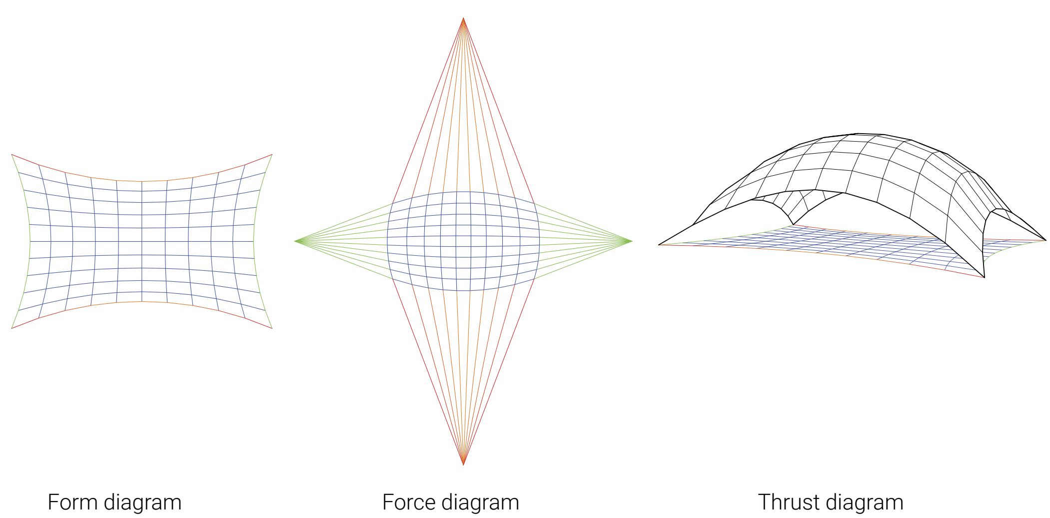
Chapter 6: Prototyping

I called this chapter prototyping because it serves as a series of tests for the assumptions I made through out the process.

Prototype 1

Form Finding

Prototype 1 was created to test whether bio-composite structure can resist load through optimized geometry form. The form finding was done using RhinoVAULT. The material was based on the pressed brick recipe developed in Chapter 3: Material Studies Experiment 3. Prototyping not only involves form design, it also involves the fabrication of building blocks and construction. While all three aspects are important, prototype 1 focuses on fabrication of building materials and construction. The form is a simple vault with 4 point supports. Prototype 1 is a 1:20 scaled model of a 4m x 6m vault, which results in a 20cm x 30cm vault in model.



Thrust diagram with its projected form diagram and corresponding force diagram

RhinoVAULT uses color to represent stress gradient in the diagrams which makes it very clear where the most stress lies in the form. Red represents greatest stress and blue the least stress. As shown in the diagram, the two longitudinal opening will have the most stress.

Building

Brick and Mortar

Brick matrix used was 200ml 9% Xanthan gum, 250ml eggshell, 150ml ground woodchip and 100ml biochar. The mixture was dry because of the increased biochar and ground woodchip content. About 30ml water was added to the mixture to ensure workability.

Mortar was 60ml 9% xanthan gum and 90ml eggshell.

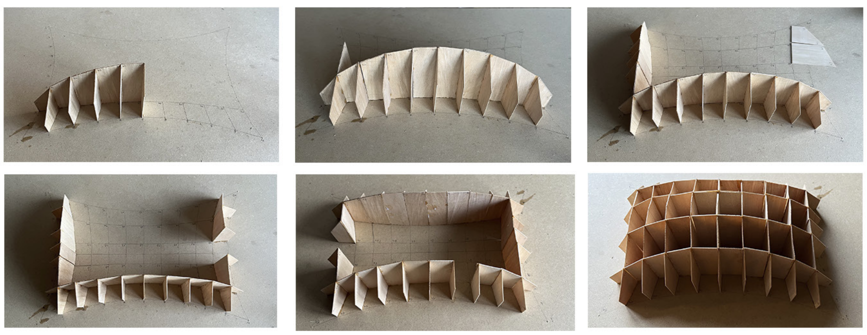
Because of the scale of the model (20cm x 30cm), I could not really make a component small enough to be considered a tile in comparison. The building blocks would be considered bricks in scale. The method employed making the bricks was inspired by the Mexican tile making method in which a block of material is rolled out with a rolling pin against two strips of wood that register the thickness of the tiles. After the mixing of ingredients, the mixture was rolled out to 1/4 in thickness and then cut to 3.5cm x 1.5cm blocks. Each block was check against a dimension guide for further reshaping before put on the drying rack.

Building Falsework

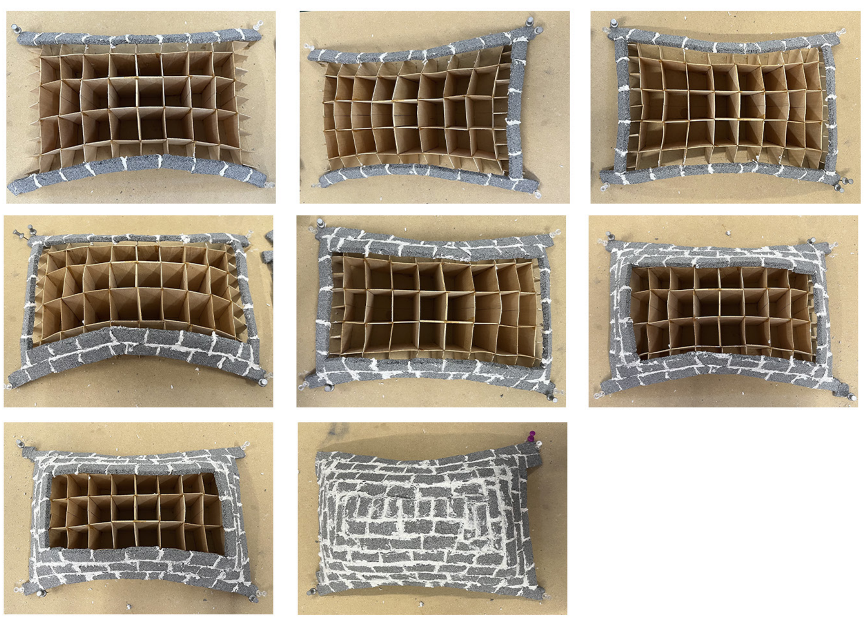
A full set of falsework was built with wood to show the geometry the brick needed to follow. The falsework also provided temporary support while building. I did not know how to consider the decentering mechanism at the time of

Brick Making

Falsework Building



Vault Building



Prototype 1 building process

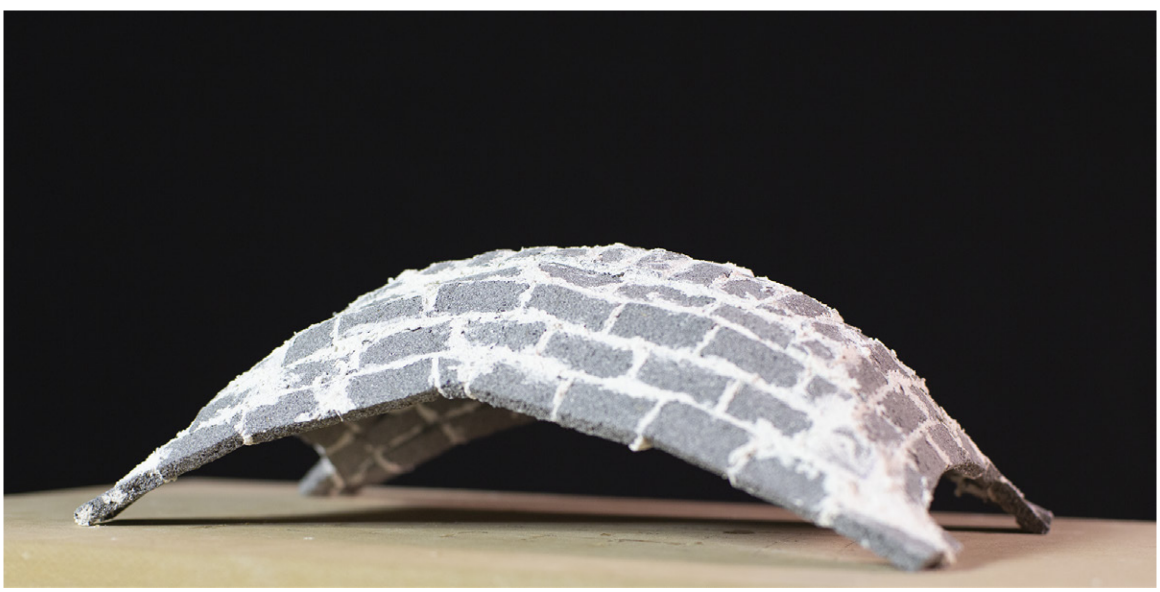
building so the removal of the formwork after finish building presented some difficulties.

Building the Vault

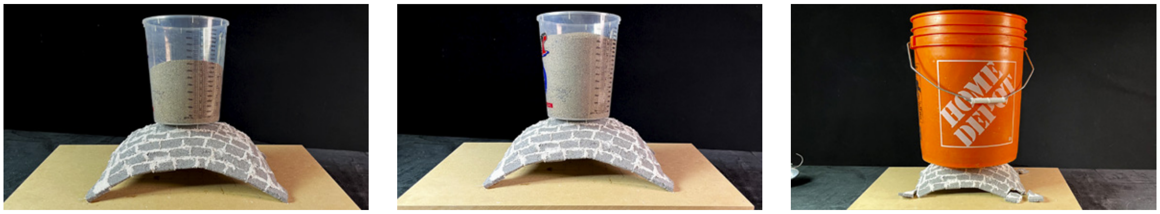
The actual vault building started from the boundary and built inward. Once the first two long boundaries were built, the process became easier. The application of mortar was a difficult task. It took a bit of practice to apply just the right amount. The mortar was made with the same base--Xanthan gum and eggshell, it provided a good adhesiveness to the bricks. Although the mortar was not fast setting, it did not pose any problems because the falsework provided support for the structure.

Decentering

The decentering process was essentially a process of destroying the falsework. Fortunately, the bio-vault was light weight and it did not rest on the falsework after the mortar dried. I was able to dig the falsework out without collapsing the vault.



Finished vault perspective



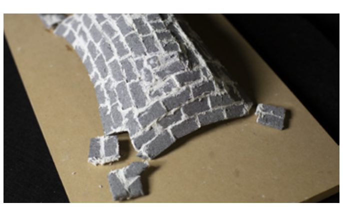
From left to right: 2kg load test, 3kg load test, and 6kg load test

Load Test

The finished vault underwent a series of load test. Started with 500 gram of water and increased to 2 kilogram of water. After 2 kilogram, water became too difficult to balance on top of the vault so sand was used in replacement. Load was applied at 1 kg increment until three corners of the vault broke outwardly at 6 kg load. But the remaining structure withstood the 6 kg load.

Critical Analysis

Broken corners front



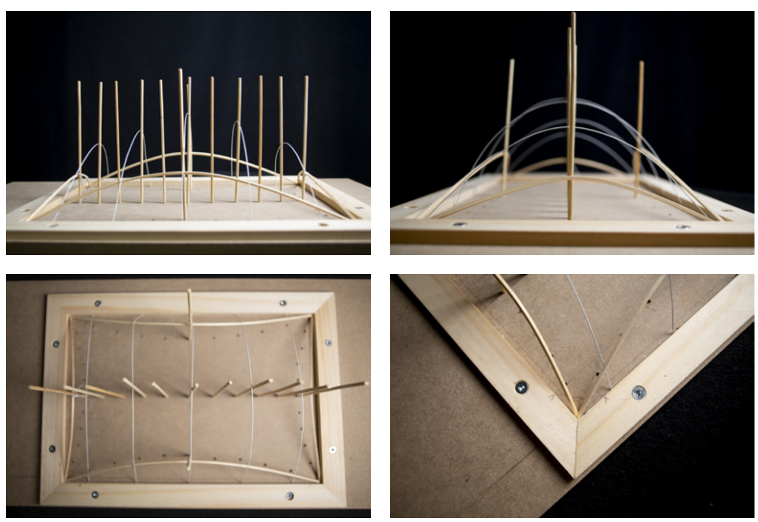
Broken corners top

It was evident that bending happened at the corners. The load from the 6 kg bucket thrust the corners outward and caused the thrust line to be out of form. A fixed base at each corners that can provide the counter reaction may have allowed the vault withstand more load. Supporting the entire vault on four points did seem to pose a problem especially when scaling up. Solution could be made by increasing the footing size. It was also observed that breakage happen at mortar joints. A Guastavino tile vault usually has 3 layers of tiles sandwich 2 layer of cement mortar. Each layer of tiles are laid at an angle to the previous layer to avoid a continuous mortar seam. Since this prototype only has one layer of bricks, breakage at the mortar joint was almost inevitable.

Falsework Iteration

The falsework generated to build prototype 1 became waste. If the vault was built to its actual size of 4m x 6m with this method. The amount of waste that will generate from the form work will be tremendous, which is counter to the purpose of this thesis--to stop waste being produced in the first place.

An effort to reduce the falsework was made. A plan of the form diagram was drawn directly on the base. Each point on the boundary curve on the form diagram was inserted a bamboo skewer of the same length (representing a dimensional lumber or steel pole), corresponding height was marked on each skewer. A frame that circumferences the base was put in place. Four pieces of wood were soaked in water and then bent following the marked height and converge at the four corners. The bent wood defined the shape of the four openings of the vault. The skewers along the boundary curve were then removed except for the ones



Falsework iteration that reduced the amount of material used.

that marked the highest point of each opening. Another set of skewers along the long center line were inserted and marked height of the intersecting vault. Metal wires were cut to length and placed along the short end of the vault at intervals. The intersecting point of the wire and the skewer represents the height of the vault at that point. The frame is designed to be removed after the tiles are laid. This iteration reduce the amount of material needed for the falsework.

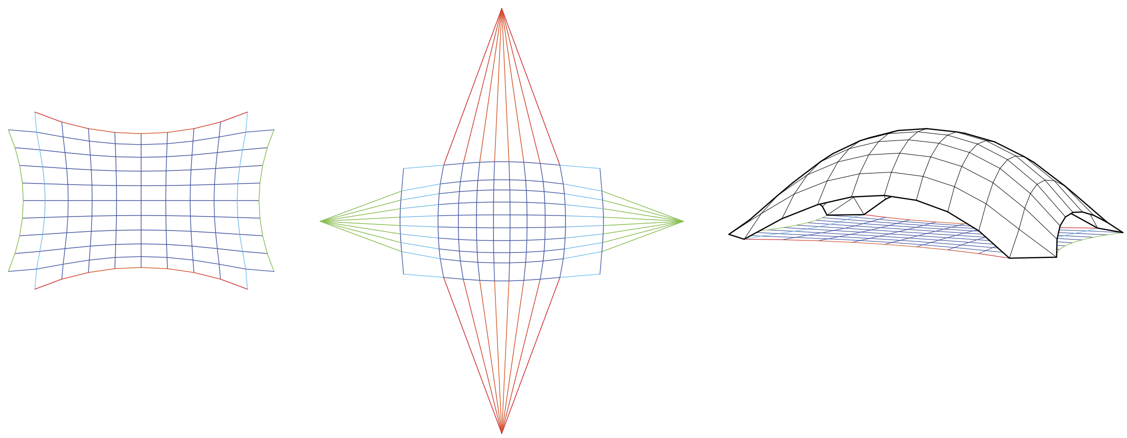
Prototype X

Based on the critical analysis of prototype 1, a series of intervention were explored. The method was a combination of digital and physical modeling. The binder used for tiles made for prototype 2 onward was changed to casein lime binder for the reasons discussed in Chapter 3.

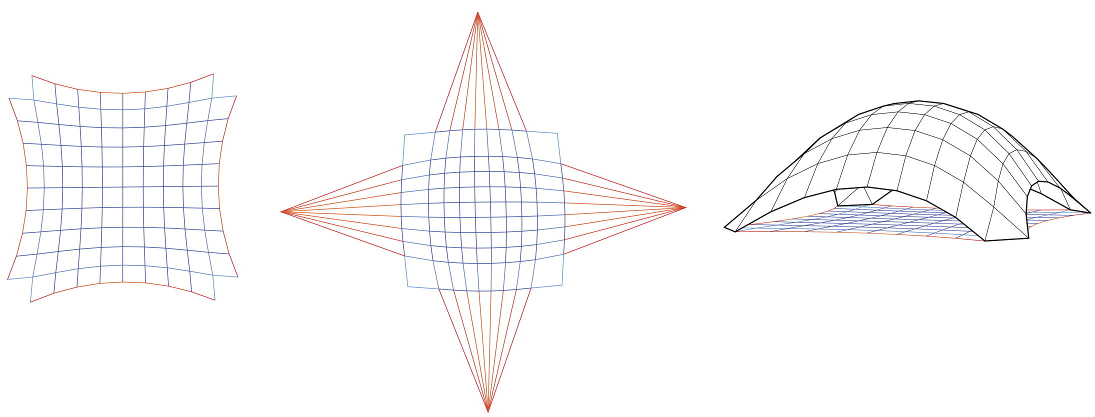
Digital modeling focused on resolving the footing issue with consideration of the final prototype size. Form diagram was modified to change point footings to flat footings. Considering the buildability of the final prototype within the constrain of time, the vault base changed from a rectangle to a square for simpler construction. Decision was also made to build a quarter of a final prototype (2.4m x 2.4m) to represent materials, form and construction. The size of the quarter prototype is approximately 1.2m x 1.2m x 0.9m.

Because a quarter of a vault is not a full vault, the dynamic of forces changes. At midpoint where the frame intersect with the vault, there will be thrust against the frame that the frame will counter. To better understand how this dynamic works, two sets of construction mock-ups were conducted.

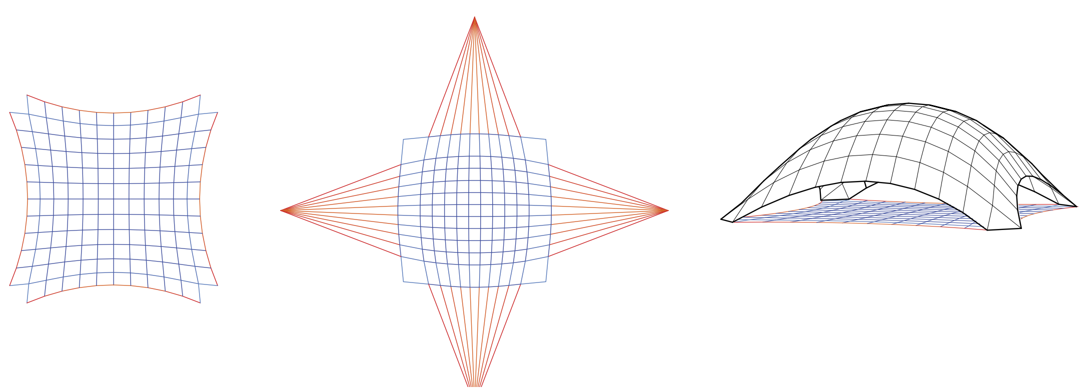
Prototype 2 vault base 2m x 3m, vault height 0.9m



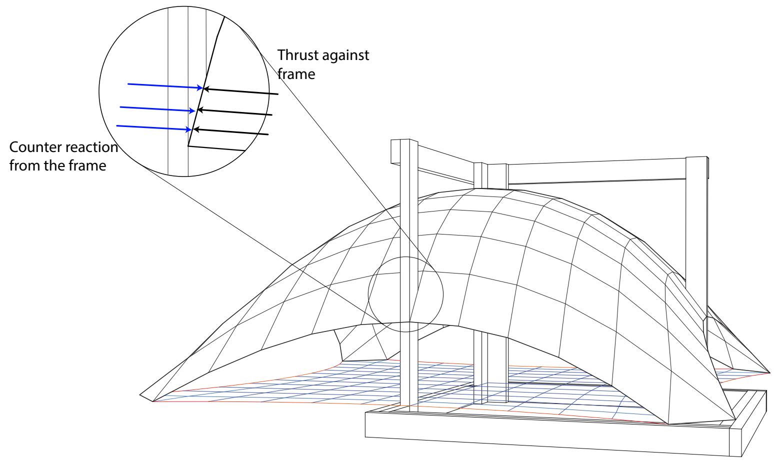
Prototype 3 vault base 3m x 3m, vault height1.2m



Prototype 4 (final prototype) vault base 2.4m x 2.4m, vault height 0.9m



Prototype 2-4 with different vault base and height.

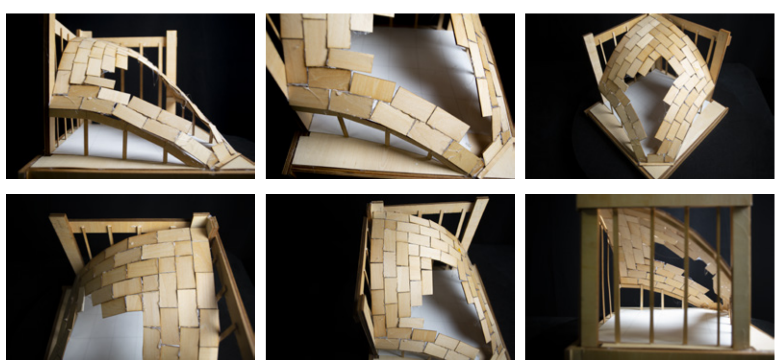


Framed a quarter of the 2.4m x 2.4m vault, resulting in an approximate 1.2m x 1.2m x 0.9m vault.

Construction Mock-up 1

Mock-up 1 was a quarter in scale to the final prototype. Information obtained from Mock-up 1 are as followed:

- Vault can be built by first building the 4 boundary curves and building inwardly.
- Vault can be built top-down.
- Challenges were encountered using orthogonal tiles to define curve, shown as gaps between tiles .
- Intersecting frame is emphasized over vault.



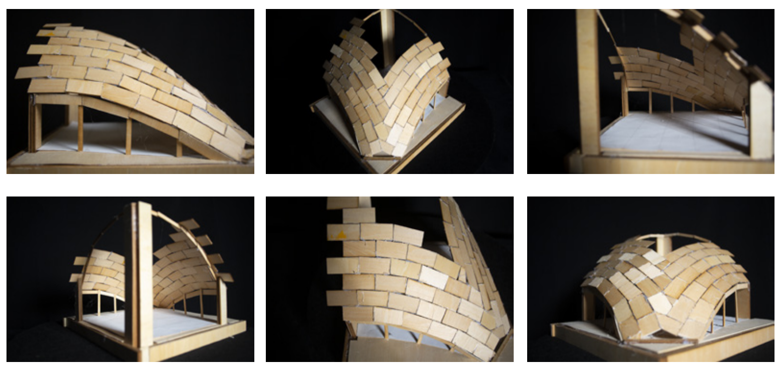
Mock-up 1 photos showing the overall presentation and construction challenges.

Construction Mock-up 2

Issues found from Mock-up 1 were addressed in Mock-up 2 as followed:

- Frames were cut below the vault to reduce visibility.
- Excessive frames were removed to reduce clutteredness.
- Tiles were cut at an angle along the long side to better follow the curve.
- Overall presentation emphasizes the continuation of the vault.

I gained much practice and confidence from building the prototype and mock-ups. These experiences prepared me to build the final full size prototype with anticipation for challenges as things scaled up.

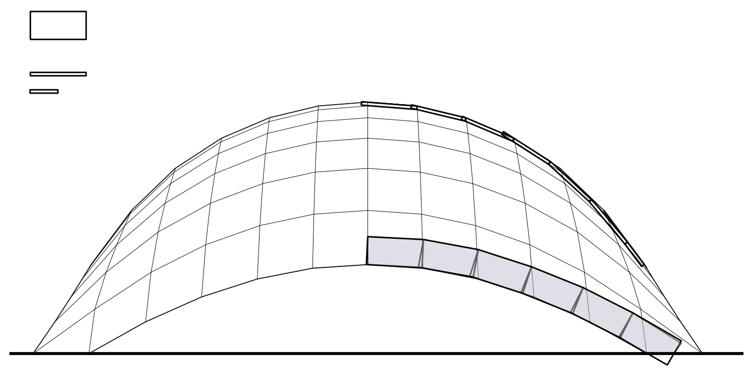


Mock-up 2 photos showing the resolved issues.

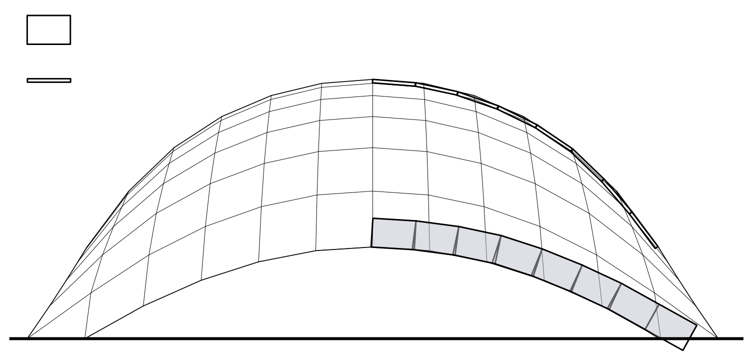
Chapter 7: Final Prototype

Tile Sizing

It was learned from the two construction mock-ups that individual tiles needed to be cut at an angle to better follow the curve. A different tile dimension was also explored to find the optimal tile size for the final prototype. The smaller size 15cm x10cm x1.2cm was found to better follow the curve which will produce less waste as most of the tiles will be cut. Smaller size of tiles minimized shrinkage along the long side



Tile dimension 20x10x1.2cm

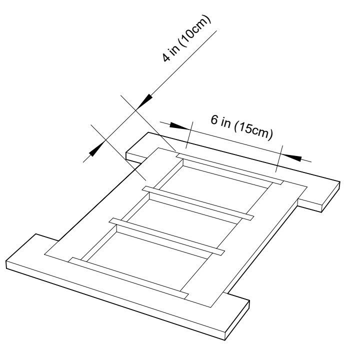


Tile dimension 15x10x1.2cm

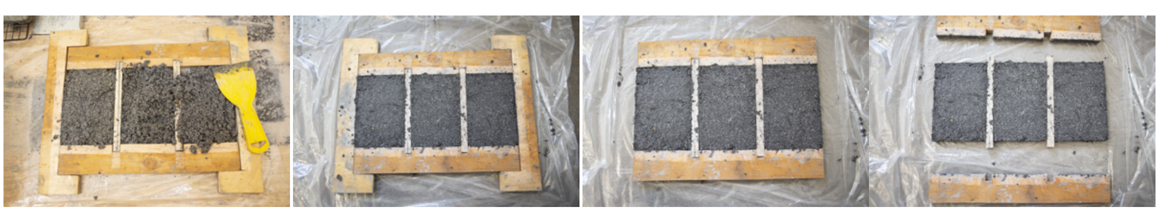
during drying which allowed more consistent result in tile dimension. Thirdly, the 15-cm size fits in my hand perfectly, which allowed smoother construction.

Tile Production

A fast release mould was designed to ensure a time-efficient work flow of the tile production. Batch size was set to be 4 cups (approximately 1 L) from experience for maximum workability. Recipe used for tile was discussed in Chapter 3. Lime was prepared with equal volume of cold tap water and stirred until dissolved. Freshly made casein was added to lime water mixture and allowed 10 minutes for casein to dissolve. Dry ingredients were then added to mixture and mixed by hand until homogeneous. Woodchip was added last to the mixture to achieve desired consistency (resemble a very thick pancake batter). Mixture was pressed into fast release mould. A mortar trowel was used to flatten the surface, following a manner of pressing from the center outwardly against the wall of the mould. Once all corners were filled and a flatten surface was achieved, tiles were released from the mould and left on the work surface to dry for a few hours. After a few hours, the tiles are stable enough to be transferred to a drying surface to dry. On the average, It takes about 7-10 days for the tiles to dry, during the period of time, tiles were flipped sides every 8 hours to allow even drying and minimize warping.



Drawing of fast release mould

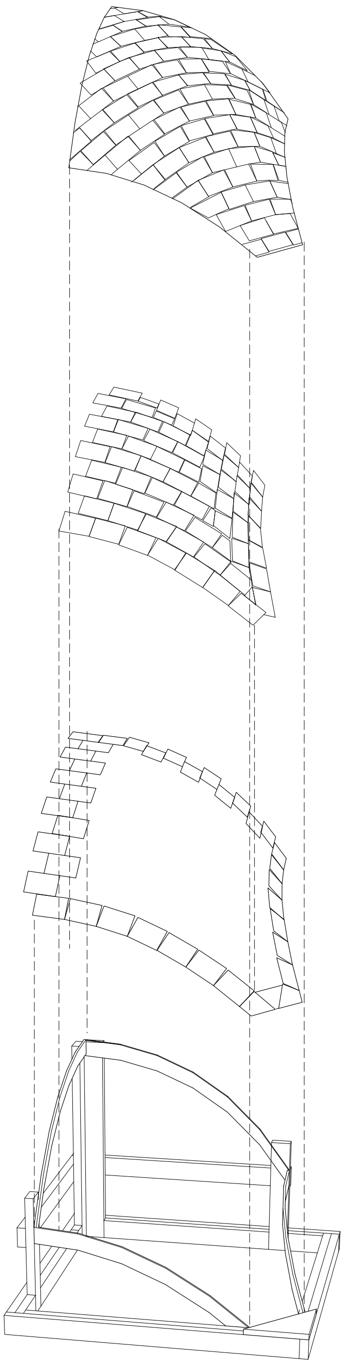


Fast release mould working in action

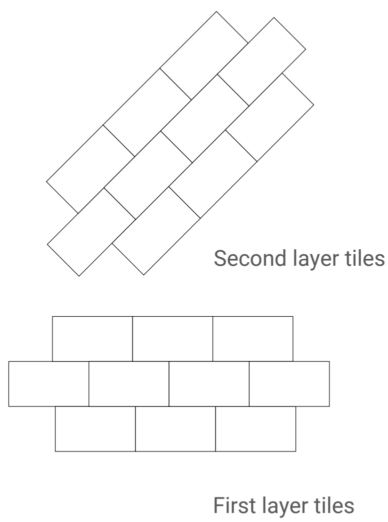
Building

Construction Workflow

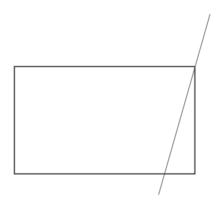
The falsework for the final prototype was further reduced to only four boundary curves. The two boundary curves that met the base were constructed first, using a customized fast setting mortar. The other two boundary curves and infill were built simultaneously using the first two curves as guide and temporary support. Once the first layer of vault was in place, the building of the subsequent layer became relatively easy. Tiles were laid top down and rotated 45 degrees to the first layer to avoid a continuous mortar seam. A one-way cut system was also employed to cut individual tiles either on the long side or short side depending on the direction the tile was going so the tiles can better follow the curve.



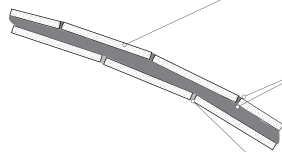
Final prototype construction workflow



First layer tiles are staggered to avoid a continuous mortar seam; second layer tiles are rotated 45 degrees and also staggered.



Use one-way cut system to adjust the shape of the tile to better follow the geometry.



Section of a segment of vault showing the material composition.

Vault Material Composition

The vault has three layers: one layer of bio-mortar sandwiched by two layers of bio-tile. Employing the Guastavino tile vaulting technique, the first layer of bio-tile uses a customized fast setting mortar. Sandwiched layer and the second layer of bio-tile uses a Lime biochar mortar, also customized.

Fast Setting Mortar

The fast setting mortar played a very important role in the construction workflow. Without it, the vault would not be constructed with such minimal falsework. A customized fast setting mortar was used for the construction of the first layer. The base is DAP Plaster of Paris that can be purchased at local hardware store. Once mixed with water, the average setting time for DAP Plaster of Paris is 6-10 minute, which means that I have an average of 6 minutes of work time. The short work time also means that I have to mix in small batches. The Plaster of Paris on its own did not adhere to my bio-tile very well. I modified the mixture by adding about 1/6 in volume of biochar to each batch of plaster. The modified recipe reduced the set time to 3-5 minute and had better adhesion to the bio-tile. On an average, each tile needs to be held against the preceding tile for 1 minute before it cantilevers.

Lime Biochar Mortar

A customized lime biochar mortar was used for the sandwich layer and second layer of bio-tile. The base recipe is one part of lime to 3 parts of biochar, adapted from a traditional lime sand mortar mix design (Allen and Allen 2003, 16). Casein was added at 0.3 to lime volume ratio to increase workability as well as reduce curing time. Lime biochar mortar was not only used to adhere the second layer tiles to the first layer, it was also used to level any uneven surface to avoid gaps between tile and mortar.

Finished vault perspective view

View from footing upward

Interior

Opening edge condition

Vault construction process photos

Vault	**Quantity**	**Unit Quantity**
# of Bio-tile	200	
Estimated weight	46.67 kg	
Surface area	1.5 m^2	
Material Usage		
Ground eggshell	8.2 L	
Biochar	30 L	
Milk for casein	6 gal	
Lime	25.6 kg	
Time Invested		
Raw material preparation	3 wk	
Tile production	40 hr	12min/tile
Tile drying	7-10 d	
Vault building	40 hr	2.5hr/ft^2

A breakdown of material usage and time invested to build the vault.

Chapter 8: Carbon Analysis

Global Warming Potential (GWP)

The release of GHGs into the atmosphere gives rise to climate change. There are many GHGs and each has a different level of potency. Each gas is normalized relative to the impacts of one unit of carbon dioxide (Hammond, Jones, Lowrite, and Tse 2011, 6). The embodied carbon of the final prototype is estimated by multiplying each estimated material weight (kg) by its embodied carbon coefficient ($kgCO_2e/kg$) to obtain CO_2e in kg.

For simplicity of calculation, I omitted woodchip in the calculation. Woodchip is at most 10 percent of the batch volume and is considered a carbon neutral material. The embodied carbon coefficient for cement, lime, sand and ceramic tile were obtained from the BSRIA guide (Hammond, Jones, Lowrie, and Tse 2011, 10-12). GHGs for casein was calculated based on volume of milk used in fabrication and the amount of $kgCO_2e$ produced per kg of milk production (Finnegan, Goggins, Clifford, and Zhan 2017, 263). The embodied carbon coefficient for the biochar used in this study is -2.9 $kgCO_2e/kg$ based on an internal calculation done by RDA. The GHGs produced for transporting the biochar to building site was not taken into account. The number of tiles used for the calculation is 200. The amount of lime biochar mortar used was estimated based on 1L of mortar for every 5 tiles on the second layer that included the sandwich layer and mortar between tiles. There was a total of 87 tiles used for the second layer. Therefore the volume was estimated to be 17.5 L mortar. The volume was then converted in proportion to weight of each material for

Material	Density g/cm3	GHG kgCO2 e /kg	Reference
Eggshell	1	0	Lab data
Biochar	0.275	-2.9	RDA
Hydrated Lime	2.21	0.78	BSRIA
Milk	1.033	0.8-1.4	per kg of milk produced
Portland Cement	3.15	0.94	BSRIA
Sand	1.602	0.01	BSRIA
Ceramic tile	2.25-2.35	0.78	BSRIA
Gravel	2.24	0.0052	BSRIA
GWP is calculated by material weight kg x kgCO2e/kg			
Prototype	**Weight kg**	**GWP kg CO2e**	
Bio-vault (200 tiles)			
Eggshell	7.38	0	
Biochar	4.06	-11.78	
Hydrated lime	16.32	12.73	
Biochar Mortar			
Biochar	3.45	-9.99	
Hydrated lime	9.23	7.20	
Casein calculation based on raw material			
6 gallons of milk used	23.46	18.77	
	Total GWP	**16.93**	
A ceramic tile model	**Weight kg**	**GWP kg CO2e**	
Ceramic tile (biotile replacment)	66.46	51.84	
Mortar (1:3 cement to sand volume)			
Cement	13.15	12.37	
Sand	20.07	0.20	
	Total GWP	**64.41**	
A concrete thin shell of the same volume (cement:sand:aggregate 1:2:3)	**Weight kg**	**GWP kg CO2e**	
Cement	24.28	22.82	
Sand	24.69	0.25	
Aggregate	51.79	0.27	
	Total GWP	**23.34**	

Calculation table for estimated GWP of final prototype, a ceramic tile model and a concrete thin shell.

calculation. The embodied carbon for the Plaster of Paris was also omitted as the affect was minimal.

The estimated embodied carbon for the final prototype is 16.93kg CO_2e. A model that uses conventional materials like ceramic tile and 1 to 3 cement sand mortar would have an estimated embodied carbon of 51.92kg CO_2e. A thin shell concrete vault of the same volume using a 1:2:3 cement to sand to aggregate ratio would have an estimated embodied carbon of 23.34 kg CO_2e. Compare to concrete thin shell, this bio-based vault will have a 27% reduction in embodied carbon, while comparing to a ceramic tile vault, it is a 67% reduction in its embodied carbon.

The embodied carbon for casein in the bio-tile was high, but was offset by the carbon draw down capacity of biochar. I am considering the possibility of using waste stream from diary production as casein sourcing for future studies.

Chapter 9: Conclusion

It has been an enjoyable journey for me with many trials and a few victories. The final product for the thesis remains a prototype because it concluded one investigation while opened doors to others.

On Answering the Thesis Question

In the beginning I asked the question whether a bio-based material can be built as structures that has the potential for carbon drawdown. At the end of tunnel, I have demonstrated the buildability of such a structure from material study, mix design, to building component fabrication and construction of the prototype. I have also proven its carbon drawdown capacity.

Will I say that I have created a new structure material that can replace concrete? I think it is one step towards that direction. For a bio-based material to be accepted by the public as a structural material would require a lot more prototyping. I went extreme in this thesis by using all bio-based material except for the lime and Plaster of Paris. Perhaps we could start with substitution in small percentages, test it, and gain confidence then increase the percentage. Creating something new does not mean that we have to forsake everything old. There is a wealth of knowledge on modern concrete from a century old accumulation that we can draw upon. The hope is always to improve and make something better. There is an increasing number of studies on biochar as cement or sand replacement in recent years. The interest for the topic is there, perhaps this thesis can contribute to that conversation.

With regards to strength, pliability, durability and industry maturity, some possible opportunities and challenges highlighted by this study include:

Bio-based material is weak compared to concrete. But through an optimized compression only geometry, bio-based structure can support impressive amount of load as demonstrated by prototype 1. The final prototype resolved the footing issue and reinforced the vault with two more layers. Theoretically, its load bearing capacity ought to improve. But it was a quarter of a full size vault, to test the strength of the vault built with the materials in this study may require completion of the full vault first.

Like concrete, bio-based composite can through adjusting material composition to induce desired property. It can take the form of a brick or a tile. It may also be cast into a monolithic form as the design intention requires.

Casein and lime form a compound called calcium caseinate that is water-insoluble. The lime mortar contains casein has been used for centuries and has a reputation of being lasting and durable. Lime will also react with carbon dioxide in the atmosphere and form calcium carbonate over time which will strengthen the composite. It is possible that bio-based composite made with casein lime binder will be durable. Testing will need to be conducted and data collected to confirm the hypothesis.

Building with bio-based material is fairly new. There are many possibilities. This study demonstrated one possibility. As more people become interested in the topic and more researches done to support its feasibility, it will have its own system of building.

On Materials

There is a constant dialog between my physical senses and the materials I am handling that guided me through the entire design process. It is a dialog that can only be perceived by constant interactions. I think this is a vital part in architectural training. We see that the pandemic has greatly discouraged our physical interactions to people and to things. Many have grown accustomed to use digital tools to model and build. Digital modeling tells an aspect of the design while physical modeling tells another. They both have errors and neither can be replaced by the other. I see the value a material driven design process and hope through this thesis many others will see.

On Scaling up

I never realized that so many challenges can arise with scaling up. Things are bigger, they are heavier, they fall faster, they change more, there are so many of them and it takes so much longer. But having a sense of what scaling up does to design is such a valuable experience for an architecture student. It helps better prepare a person for the real problems in the real world.

On Construction

Over half of the time for this thesis was invested in construction. Many of the decisions and assumptions were made based on the constructability of the prototypes. To name a few, the tile size, the shape of the tile, the vault dimensions, what type of falsework to built and what construction sequence to follow. This thesis can easily turn into an investigation on construction techniques and workflow. The understanding of the constant feedback loop between design and construction was another valuable experience I gained through this thesis.

On Other Pathways

There are certainly many other pathways that can be explored as I have listed a few at the beginning of Chapter 3. Because of the time constrain of this thesis, I have made decisions based on past and newly acquired knowledge, resource availability and time I can allot for each exploration. I hope to be able to explore some of these pathways in the future.

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