WASTE ILLUMINATES WORLDS

Printed Modular Lamp Design Based On Brick and Clay Tile

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By
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Preface

Finally, you've managed to find some time to sit down in a chair facing your laptop, searching for literature on sustainable development. On your plastic table sits a cup of hot coffee in a disposable paper cup, while the heater warms your room. At first glance, everything seems to embody peace, comfort, and safety. But is there a more compelling picture of these ideals?

Let's take a closer look. First, the comfortable chair you're sitting on. Were you aware that its fabric contains mutagenic materials, heavy metals, and dangerous chemicals? As you shift in your seat, particles of the fabric abrade and are taken in by your nose, mouth, and lungs, hazardous materials and all. Were these listed when you ordered that chair? The laptop you're using contains more than a thousand different kinds of materials, including toxic gases, acids, plastics, and other additives. Some of these materials are essential for the laptop's operation. What happens to them once the laptop becomes obsolete in a few years? You'll have little choice but to dispose of it, and both its valuable and hazardous materials will be thrown “away”. By choosing to use a laptop, you've unwittingly become part of a cycle of waste and destruction.

The production of your disposable cup has consumed a large amount of trees. The heating in your room not only consumes a vast amount of energy but also emits greenhouse gases that impact the environment. But wait a minute—you care about the environment as you have chosen to read my thesis. I will show how we can repurpose waste, specifically construction and demolition waste at this moment, to produce functional products. However, my contribution is just a small aspect; contributions from you, the readers, in other areas are also needed. Only through our joint efforts can human industry have the potential to change the current trajectory, which is seeing a decline in almost every ecosystem on this planet.

Introduction

The building industry in the New England area is often in a state of entropy, with abandoned brick buildings contributing to urban decay. The recycling rate of brick and clay tile wastes generated by construction and demolition is only 12.2%, meaning the majority is sent to landfills. The expansion of landfills can lead to significant environmental and community challenges, including increased traffic from waste transport, habitat destruction, ecosystem degradation, and contributions to climate change. Specifically, the Bethlehem landfill in New Hampshire, which is planned to undergo a 5.71-acre lateral expansion through 2026, has already encountered issues such as leachate spills and water pollution. These problems underscore the necessity of proper waste management practices to mitigate potential negative impacts on the environment and local communities.

This thesis explores the use of various biocements for the adhesion of brick and clay tile grains, examining their bonding mechanisms under Scanning Electron Microscopy (SEM). The material application of the modular lamp which incorporates digital printing technology not only minimizes waste through precise material usage but also creates special textures and remind users of the importance of protecting our planet. The creation of this lamp contributes to environmental sustainability by diverting still-usable materials away from landfills, reducing the energy required in the manufacturing process, and decreasing the demand for clay extraction, which makes sustainability development tangible.

In general, the focus of the thesis is on using recyclable rather than extractive materials to create amenities that enhance human comfort while preserving the characteristics of traditional materials and extending the history of clay in New England from a new perspective.

In general, the contributions of my thesis are in the following areas:

- Conducts material research on clay and brick, proposing a method to repurpose construction and demolition waste from bricks and clay tiles using bio-cements.
- Bio-cements that are researched can be categorized into four types: Polysaccharides (Alginate and Sugar), Chemicals (Calcium Oxide), Proteins (Urine, Casein), and Others (Resin). Among these, Calcium Oxide bio-cement also has the ability to absorb carbon dioxide from the environment. The bonding mechanisms are also observed under the Scanning electron microscope.
- Alginate, sugar, and clay recipes are tested to produce lamps via the 3D printing technique, which demonstrates the potential of material research for mass production as well as the possibility of thin wall cross sections in the architecture field.
- A high end printed sustainable ceramic lamp composed of brick dust and porcelain is proposed, which can reduce the landfill while producing the lighting solution. The final choice of a 50% clay and 50% tile dust (brick dust) composition for lamp design was based on its stability and convenience In the current state. Casein stabilization is the preferred bio-cementation method in the future practice as the results show it is water resistant, and it is a cheap and readily available waste material.

Keywords: Clay; Clay Tiles; Brick; Construction and Demolition Waste; Ceramic Waste; Sustainability; Biocement; 3D Print; Lamp; Regeneration.

Chapter One

Context and Background

The beginning of the thesis originates from a site visit to Barrington, RI on September 14, 2023.

Three centuries ago, Barrington was known for its extensive clay deposits. From 1847 to 1943, bricks were commercially produced in Barrington at the location of the present Brickyard Pond, with an estimated production of about 1.5 trillion bricks. In 1943, the clay supply was exhausted, leading to the clay pits being filled and eventually forming Brickyard Pond.

During the Barrington field trip, I noticed that suburban families often have large yards with various amenities like swings, basketball hoops, and playgrounds. However, these man-made objects' material and form look different from their surroundings.

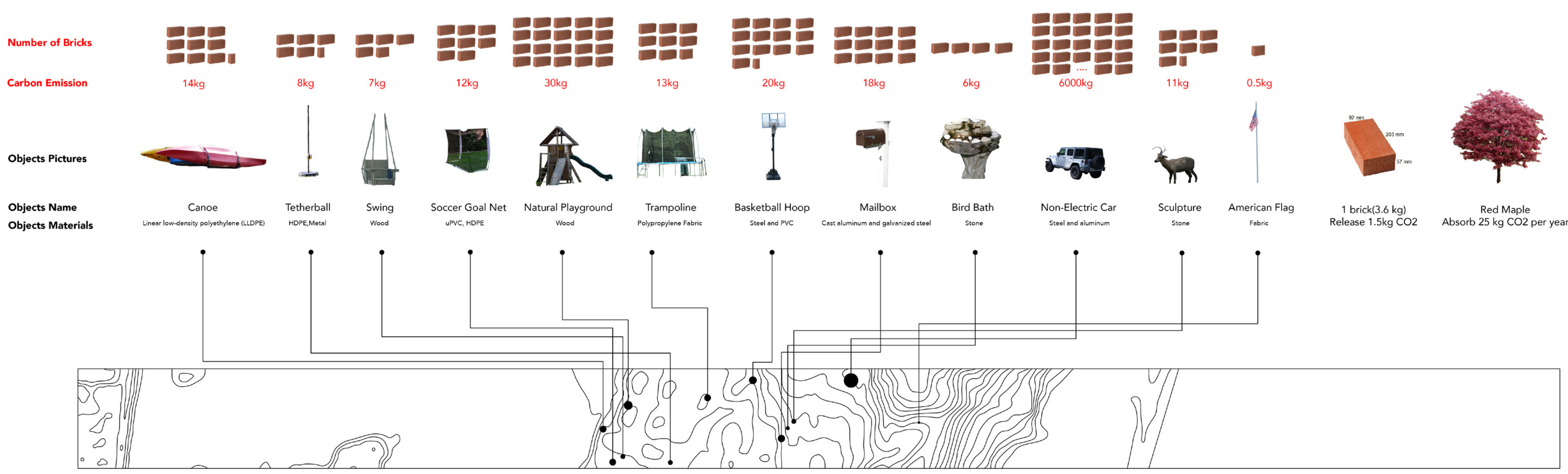
Based on Barrington's historical background, I connected clay bricks with these objects by using the amount of carbon dioxide produced during their production as a mediator. Thus, each industrial object represents a certain quantity of clay bricks. This site visit laid the foundation for my awareness of greenhouse gases and climate change.

Figures 1 and 2 depict my site visit in Fall River, MA, specifically at the Narrows Center For the Arts housed in a former American Printing Company mill building. Its basement is abandoned and contains a significant amount of demolition waste, including bricks and clay tiles. This is just one example of the repurposing of abandoned mill buildings in Fall River, with many others awaiting new life. This site visit prompted me to ponder: How can we repurpose abandoned mill buildings? (How can we reuse demolition waste?)

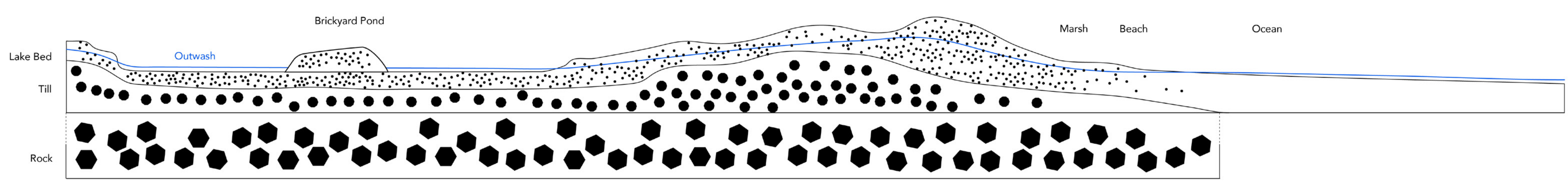
Combining the impressions from the two site investigations in Barrington and Fall River with my background in industrial design, I aim to repurpose demolition waste to design sustainable products using environmental-friendly materials.

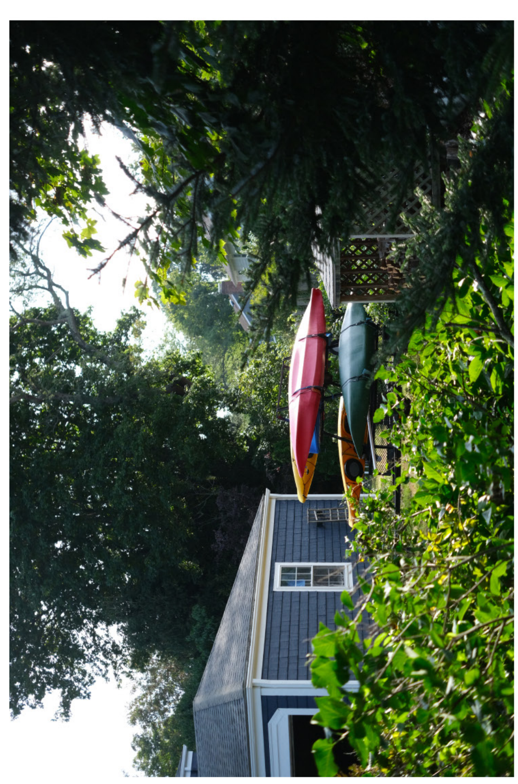
Bricks As Currency

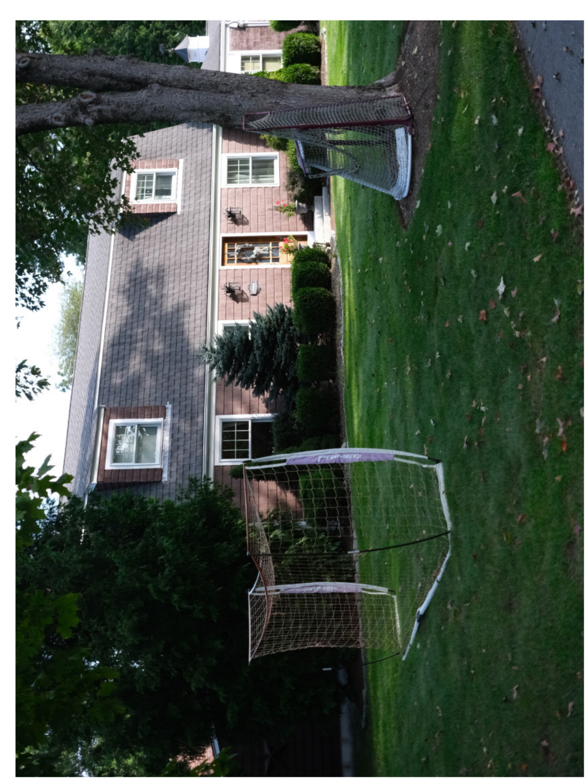
Making one standard clay brick with a weight of 3.6 kg releases 1.5kg of carbon dioxide. This reminded me that manufacturing 12 industrial products that I found in Barrington also releases a certain amount of carbon dioxide. Therefore, by using carbon dioxide as a measure, each industrial product can be represented by a certain number of clay bricks, which means that the 'value' of each product is related to the quantity of clay bricks.

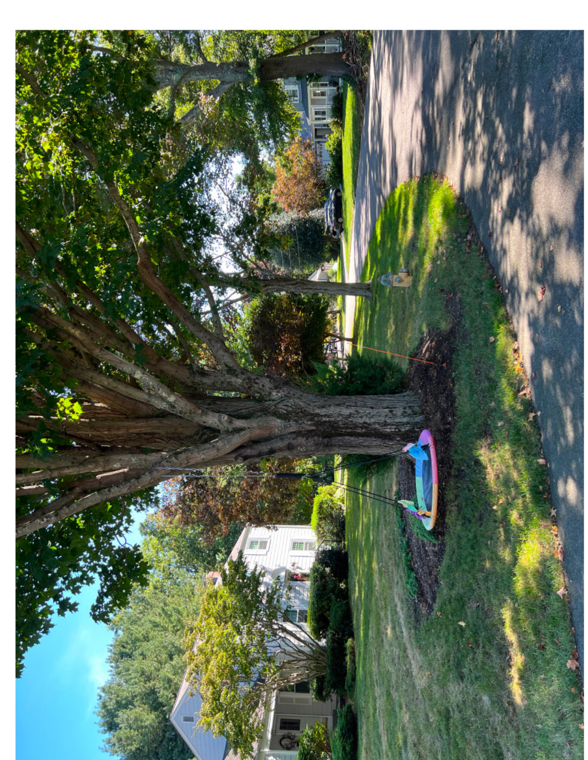


*The size of the dot is related to the amount of carbon dioxide released. The larger the dot, the higher the carbon dioxide emission.









1	2
3	4
5	6

1. Entrance of Tillinghast Place
2. Brickyard Pond
3. Basketball Hoop
4. Canoe
5. Swing
6. Soccer Goal Net

Figure 1. Narrows Center For the Arts, Fall River, MA.
Oct 5, 2023

Figure 2. Narrows Center For the Arts, Fall River, MA.
Oct 5, 2023

Chapter Two

Waste Statistics

Construction and Demolition (C&D) Waste

MATERIALS	COMPOSITION (%)
STONY FRACTION	**75**
Bricks, wall tiles and other ceramic materials	54
Concrete	12
Stone	5
Sand, gravel and other aggregates	4
REST	**25**
Wood	4
Glass	0,5
Plastic	1,5
Metals	2,5
Asphalt	5
Plaster	0,2
Rubbish	7
Paper	0,3
Others	4

Table 1. Composition of Construction and Demolition (C&D) Waste (from Juan A et al., 2010)

Construction and Demolition (C&D) wastes contribute the highest percentage of wastes worldwide (75%). Furthermore, ceramic materials, which include brick walls, ceramic tiles, and all other ceramic products, contribute the highest percentage of wastes within the C&D wastes (54%)(Juan A et al., 2010), see Table 1. The current option of disposal for this type of waste is landfill. The unavailability of standards, avoidance of risk, lack of knowledge and experience led to there being no active usage of ceramic wastes. In the United States, 600.3 million tons of construction and demolition waste were generated in 2018 (Team S., 2023). Out of this, brick and clay tile accounted for 12.3 million tons. 10.8 million tons of this were sent to landfills, resulting in a recycling rate of only 12.2%.

Tile Manufacturing Waste

Ceramic tiles are building materials with outstanding features such as high mechanical strength, wear, and chemical resistance (Sánchez-Vilches E. et al., 2010; Gabaldón-Estevan D. et al., 2014). The production of ceramic tiles as one of the popular building products grows annually and its industry is a dynamic sector whose market is growing worldwide. The manufacturing process generally consists of four stages: composition preparation, tile forming, decoration, and firing (García-Ten F. J. et al., 2016).

- During the Composition Preparation Stage, green scraps are produced. These consist of unfired materials, including rejects from the sieving of spray-dried powder, dust from the vacuum extraction system, and tiles that break before firing.
- The Tile Forming Stage leads to the generation of frit residues when there is a change in the frit composition. This waste occurs as the chemical composition of the frit becomes intermediate between the old and new formulations, rendering it unusable for immediate application.
- In the Decoration Stage, glaze sludge is a by-product. This sludge is collected from the sieving of glazes and the cleaning of glaze mills. It encompasses materials from the cleaning of glazing and decoration lines, particularly when changing the type of tile being produced.
- The Firing Stage not only produces fired scraps, which include broken tiles or tiles with defects that prevent their sale, but also dust from kiln filters. The latter is the result of capturing acidic compounds like fluorine, sulfur, and chlorine, released during firing, in compliance with environmental regulations.
- Finally, the Polishing Stage, involved in both the decoration and final finishing of tiles, generates polishing sludge. This waste comes from the operations of cutting and polishing, consisting of fired material and residues from the wear of cutting and polishing tools.

Waste Repurposing Practice

With the gradual depletion of natural resources and increasing awareness of sustainable development, more researchers and designers are engaging in the study and reuse of C&D waste materials to produce tiles and mortars. Ke, S. et al. (2016) used waste generated from the polishing process in porcelain tile production to create porcelain tiles that meet the requirements of the ISO 13006 standard. This approach allows for a reduction of up to 50% in the use of raw materials during production. Sánchez de Rojas M. I. et al. (2006) conducted extensive research on ceramic waste usage. Their focus was investigating the possibility of utilizing general ceramic rubble (mostly clay bricks and tiles) as an additive of cement and on the manufacturing of concrete-made roofing tiles. Higashiyama, H. et al. (2012) conducted research examining the impact of using ceramic waste as fine aggregates on the compressive strength and chloride penetration of mortars. Their findings revealed that mortars incorporating ceramic waste as fine aggregates exhibited superior compressive strength compared to the control mortar, which was made using river sand, for substitutions up to 20%. This study highlights the potential benefits of repurposing ceramic waste in construction materials, not only in terms of sustainability but also in enhancing the material properties of mortars. Amin S. K. et al. (2019) mixed ceramic dust waste produced by the cyclone following the spray drier in the ceramic tile manufacturing process with raw material to produce wall and floor tiles that meet the required standards.

Although the aforementioned material research presents effective methods for improving the utilization of ceramic waste, these approaches to some extend lack the scalability and potential for widespread application. As an industrial designer, my focus is to turn the construction waste into indoor products. The key to success lies in designing a product that can satisfy daily human needs while gaining wide acceptance and application. This approach is essential for maximizing waste reduction and minimizing landfill use.

Chapter Three

Material Research

Biocement Exploration

The comprehensive overview of all biocements is depicted in Figure 3. The biocements used in experiments can generally be classified into four categories: polysaccharides, chemicals, proteins, and others. The aim of this research is to explore effective and stable cement that can bind grains together for use in object production.

Due to the varied shapes and sizes of clay tiles, directly binding them is challenging. Therefore, if they are not already in smaller granules, breaking them down into smaller particles is essential. It's worth noting that due to certain lacks of a controlled experimental environment, all experiments were qualitative and they are not tested such as the strength. The contribution lies in summarizing four major categories and explain their binding mechanism to facilitate further exploration by other researchers and their potential applicability in different scenarios.

Figure 3. Overview of all biocements.

Clay and Tile

The scanning electron microscope (SEM) analysis revealed distinct structural differences between clay and clay brick (see Figure 4). Clay exhibits a fine-grained and layered structure, characterized by microscopic crystals with various sheet types, visible under SEM as thin and flat particles. On the other hand, clay brick, a building material produced through clay molding and firing, exhibits a coarse-grained and porous structure. The SEM image depicts irregular and angular particles with voids and cracks resulting from the molding and firing processes.

The firing process induces significant changes in the chemical and physical properties of clay. Notable alterations include a reduction in water content, increased strength, and a transformation in color. Furthermore, clay brick demonstrates superior compressive strength and a lower absorption rate compared to clay.

Figures 5-7 show SEM images of a series of experiments mixing porcelain (Sheffield Pottery Inc.) with brick. From the images, it can be inferred that firing at cone 05 and cone 5 did not significantly alter the chemical properties of porcelain, yet they achieved the hardness characteristic of ceramics. Therefore, it is speculated that they may still possess potential to revert to nature.

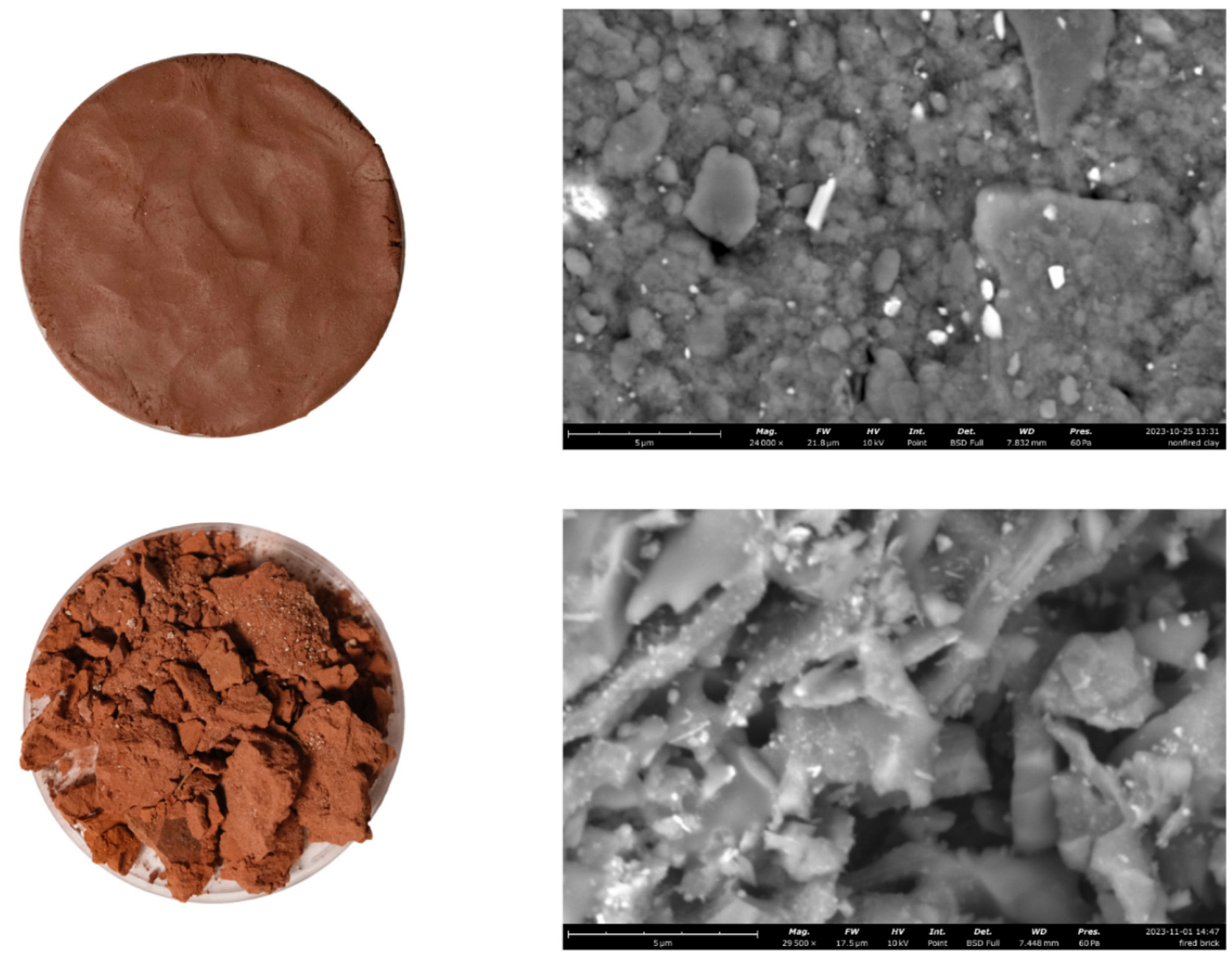


Figure 4. Structure diagram of clay (top row) and clay brick (bottom row) under SEM

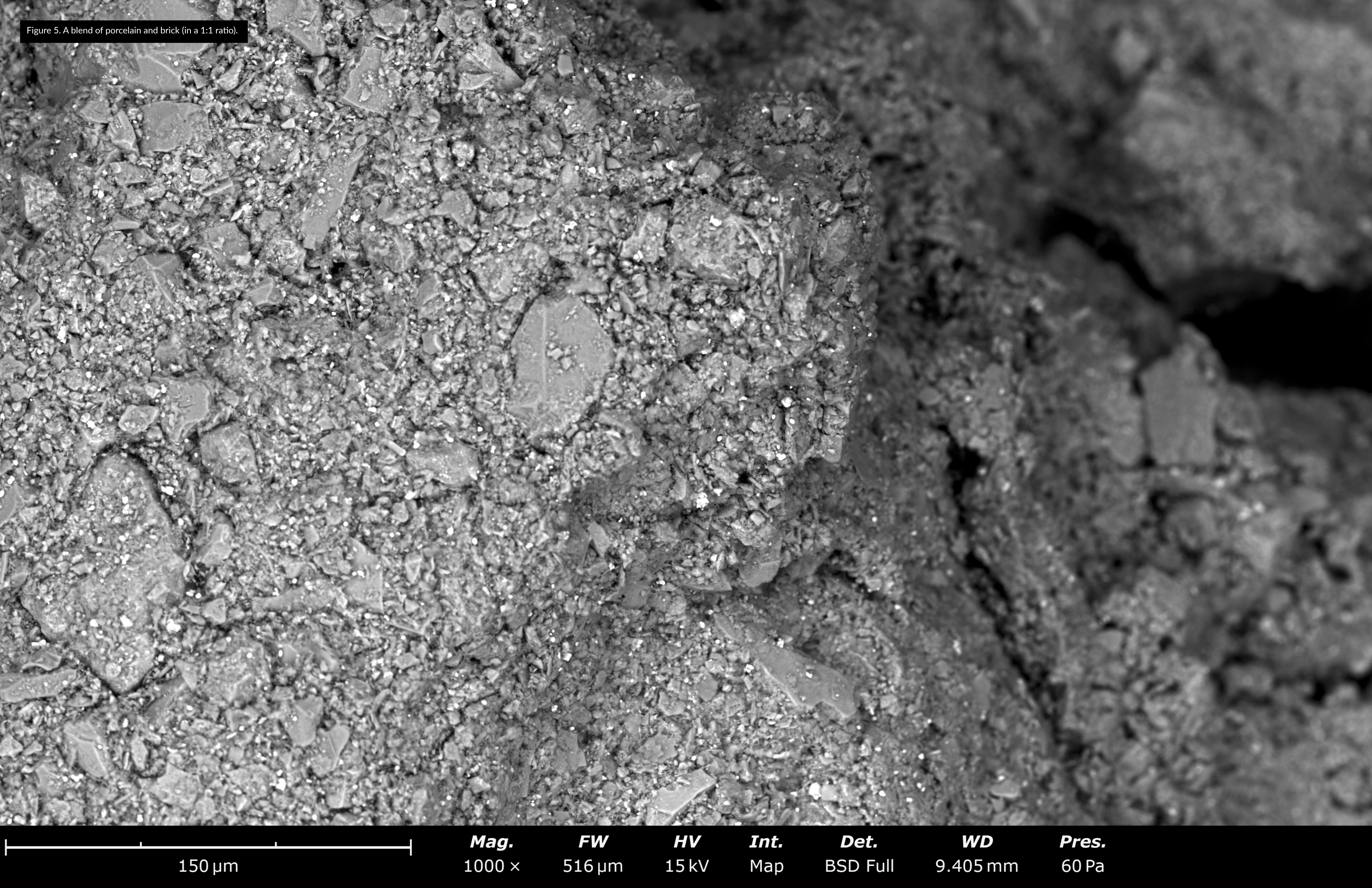


Figure 5. A blend of porcelain and brick (in a 1:1 ratio).

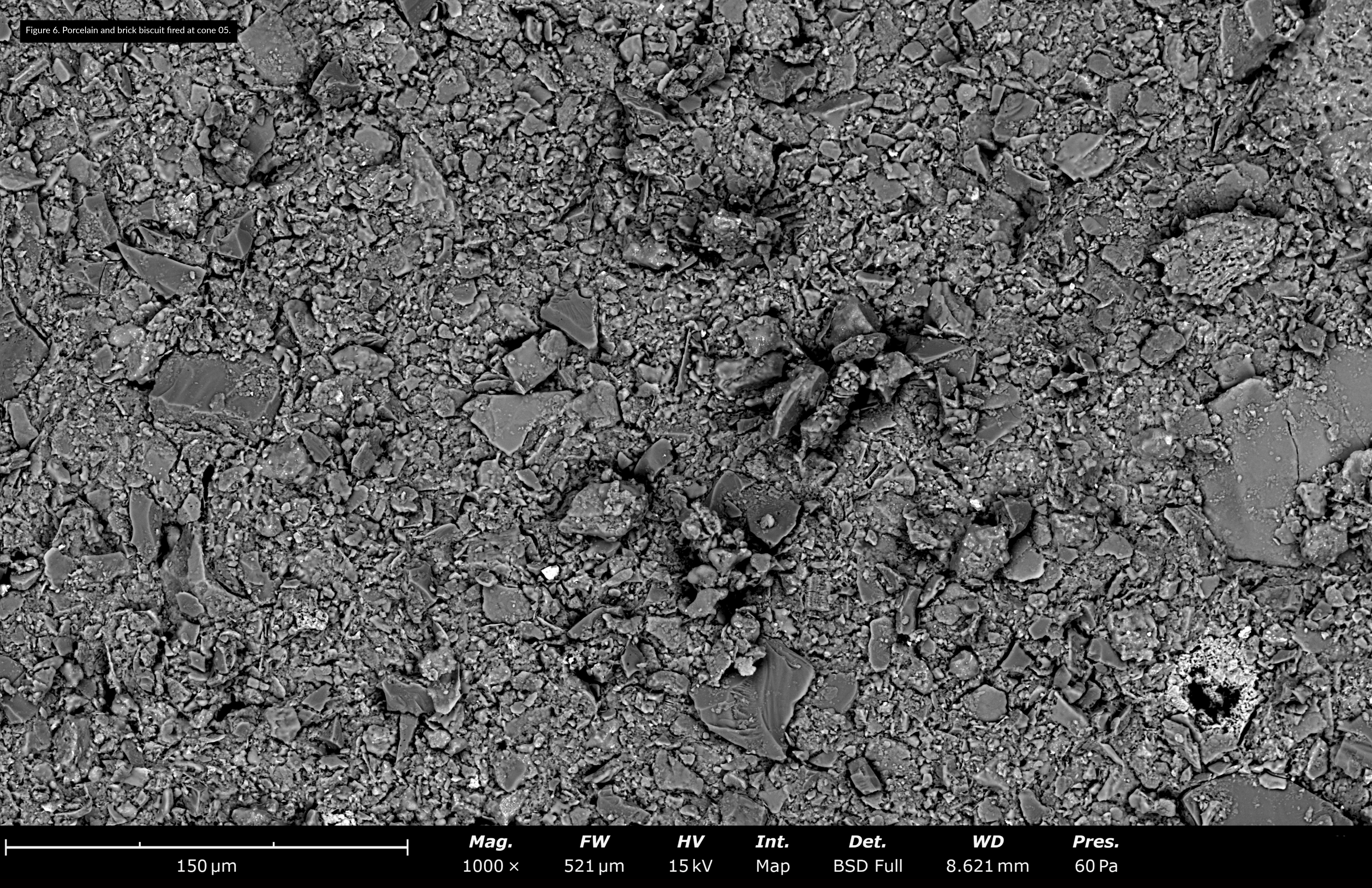


Figure 6. Porcelain and brick biscuit fired at cone 05.

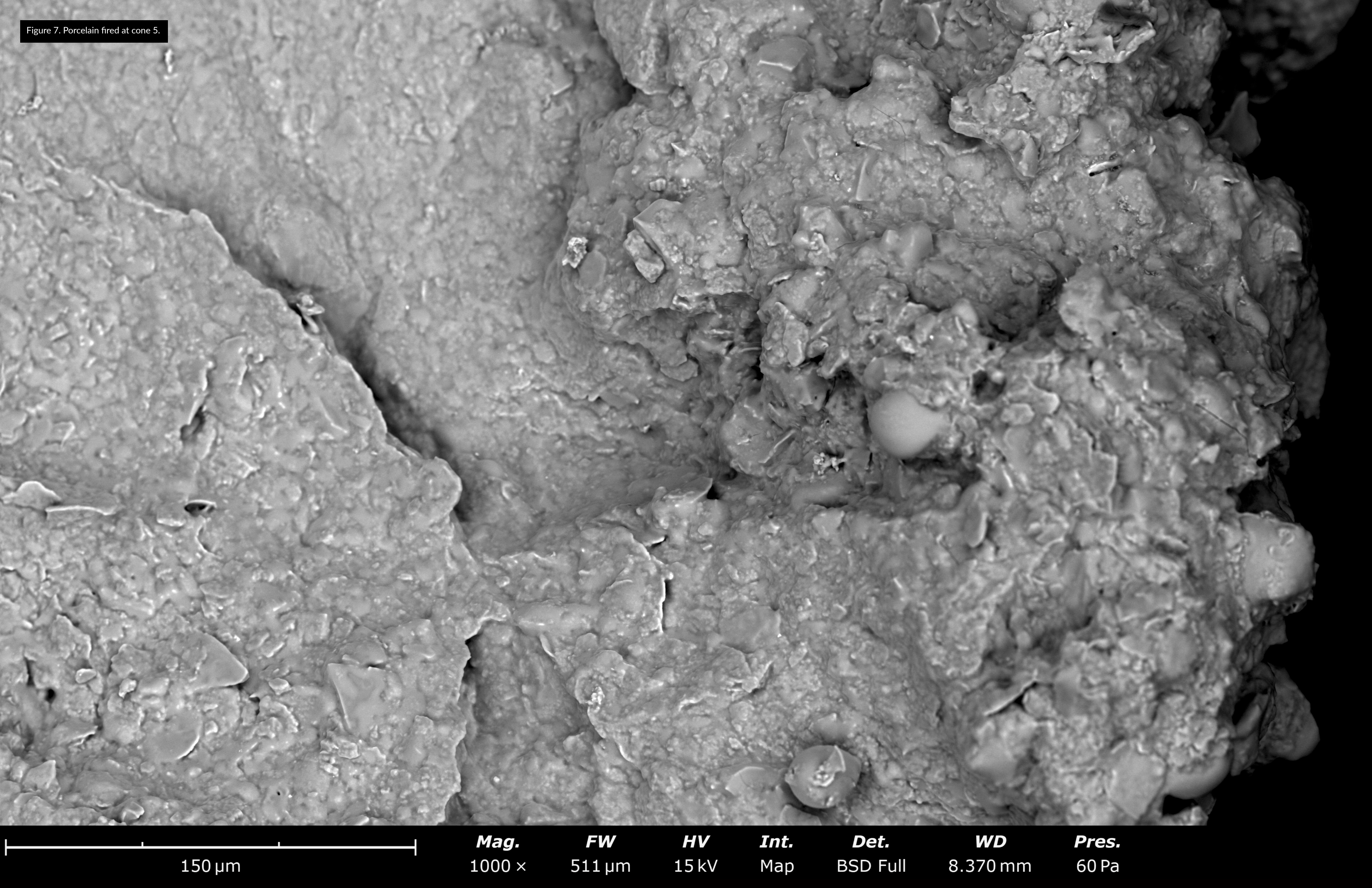


Figure 7. Porcelain fired at cone 5.

Polysaccharides Recipe

Polysaccharides, complex carbohydrates composed of long chains of simple sugars, are typically linear and sometimes branched polymers. These molecules are characterized by their considerable length and a repeating unit (ose) that consists of a ring of six carbon atoms, most of which are attached to a hydroxyl (OH) group. Polysaccharides contribute to biocement stabilization by creating microscopic frameworks among clay tile particles. Their long, intricate sugar chains can bind multiple mineral particles together, forming a network-like structure. Additionally, polysaccharides tend to form gels upon contact with water, altering the fresh mortar's consistency. The visual visualization generated by chatGPT is shown in Figure 8.

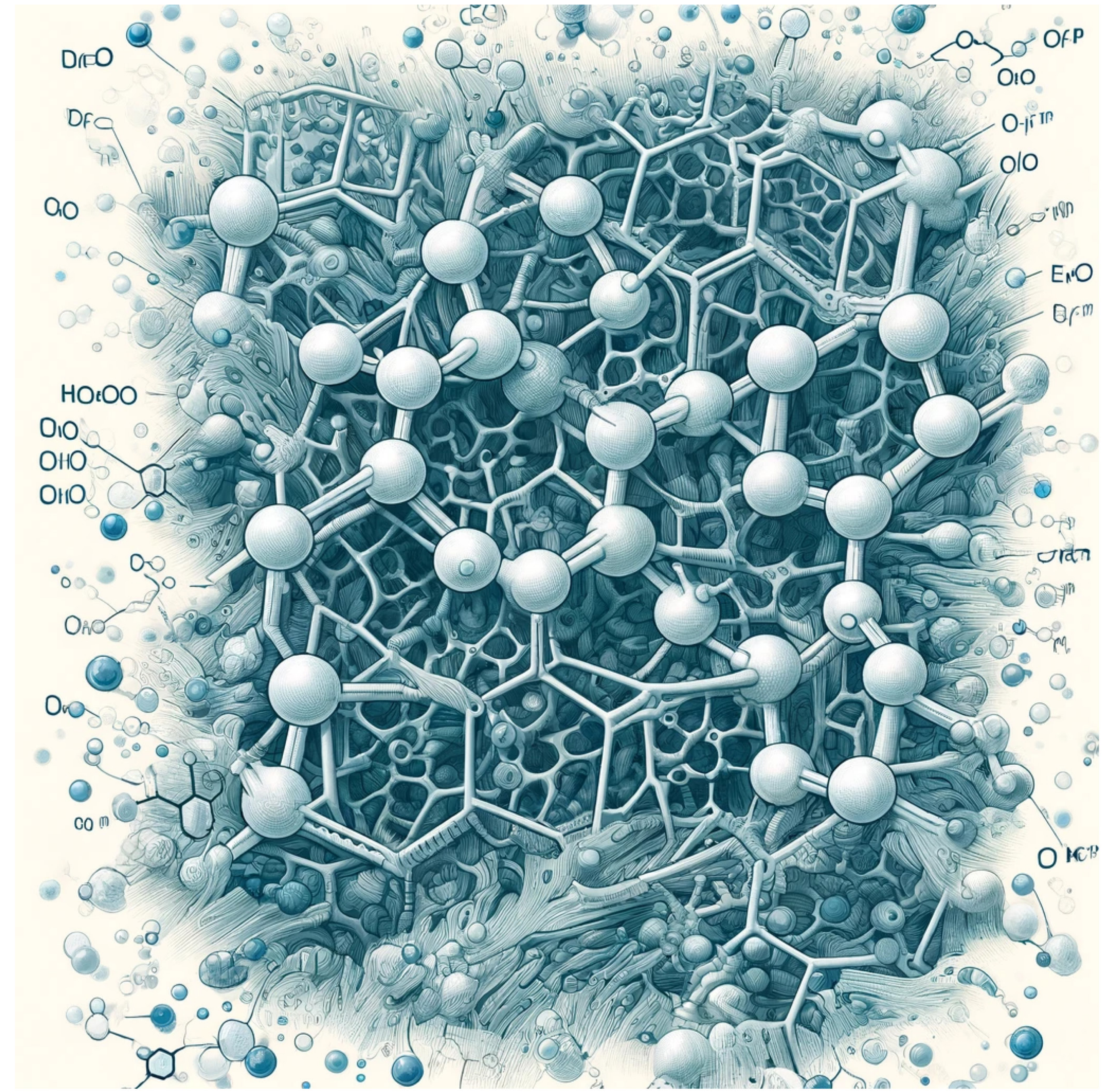


Figure 8. Principles of Polysaccharides binding brick particles

Polysaccharides Recipe

Bio Recipe - Sodium Alginate

Recipe: Vinegar 10 ml; Sodium Alginate 4 grams; Clay brick powder 10 grams.

At a macroscopic level, the underlying logic of biocement is to establish a bridge between various grains, which can link them together. I attempted to observe the appearance of this “bridge” under SEM. Unfortunately, due to the transparency of sodium alginate, it was not observable under SEM.

Sodium alginate, being a suitable biomaterial, can effectively bind grains of different sizes (0.04in, 1in). However, it experiences a 95% shrinkage in volume upon drying (0.04in), even more for 1 in. In the larger gaps of the brick, sodium alginate only adheres tightly to the surface of the brick, as can be seen in Figure 9.

Throughout this experimental process, I introduced black thermochromic dye powder. It fades at 35 degrees Celsius. The powder, observed under SEM, appears as regular spherical shapes. The incorporation of this dye turns the biomaterial into an ambient temperature indicator, which may have various potential applications.

control group ~0.04in

large grain ~1in

thermochromic dye powder

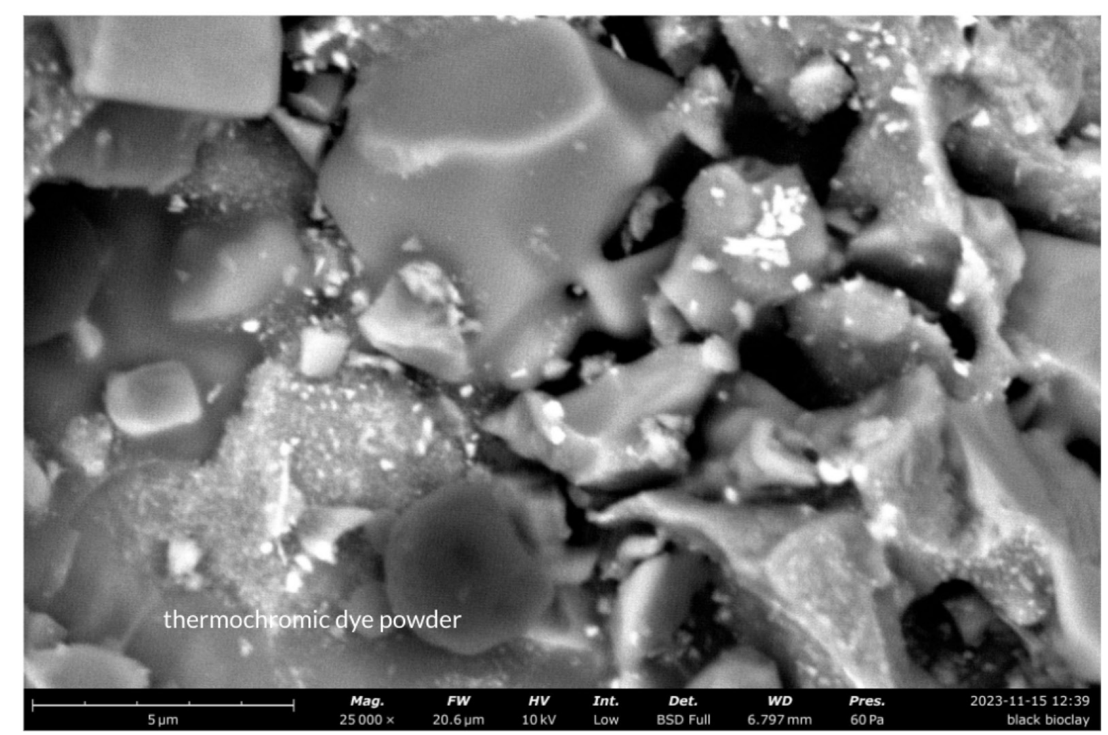


Figure 9. Prototype images of Sodium Alginate recipe (top) and the image under SEM (bottom)

Polysaccharides Recipe

Bio Recipe - Sugar

The size of these brick grains is extremely fine, which I used them for 3D printing. The sugar I used is 365 Organic Powdered Sugar from Whole Foods Market. The resulting color of this recipe is darker compared to others, though the exact reason is unclear to me. From Figure 10, it's apparent that there is black substance present under SEM, which I believe to be sugar. The highlighted part in red circles in Figure 10 clearly demonstrates the role of sugar as a biocement: encapsulating brick particles. There are no cracks visible in the SEM image, which indicates that sugar serves as a good bridge to connect the brick grains. However, this recipe is not waterproof, which means the sugar will dissolve when it is exposed to water.

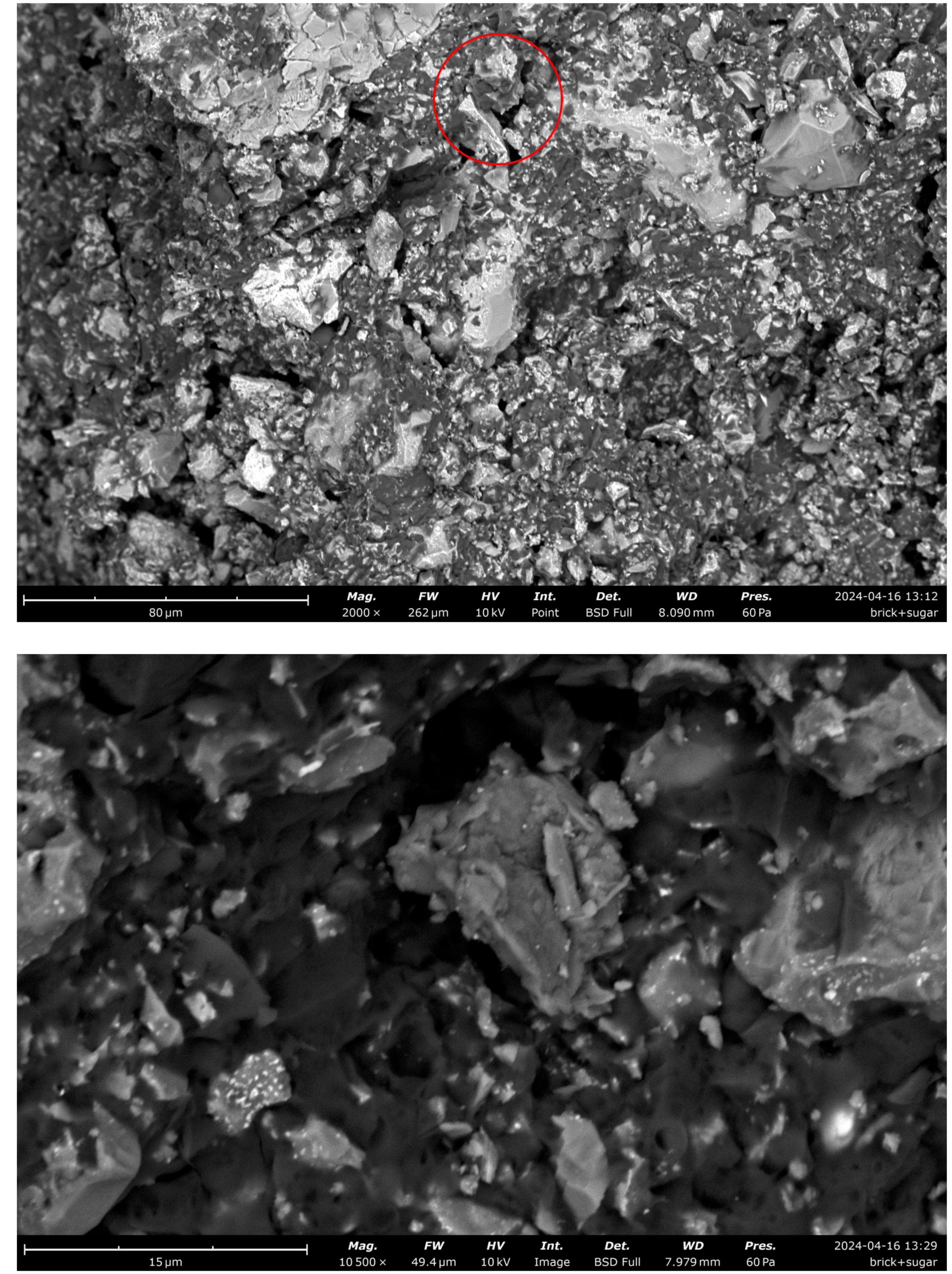


Figure 10. SEM images. Top) Magnification 2000 times. Bottom) Magnification 10500 times.

Proteins Recipe

Biomimetic Recipe - Urine

MICP stands for microbial-induced carbonate precipitation, which is a process of biomineralization mediated by specific bacteria. MICP can produce calcium carbonate crystals that can bind soil particles, fill cracks, or coat surfaces. MICP has various applications in engineering fields, such as geotechnical engineering, construction materials, hydraulic engineering, geological engineering, and environmental engineering.

A popular biomineralizing organism is Sporosarcina pasteurii (S. pasteurii). However, this bacterium is relatively expensive and I lack a suitable environment for bacterial cultivation. Therefore, I used urease, a catalyst capable of catalyzing the decomposition of urea, as a substitute for the bacteria. Figure 11 shows the SEM image of this.

grain size ~0.04in

Figure 11. Prototype image (top); SEM image (bottom left); Biocement working principle diagram (bottom right)

Let's take a closer look at the chemical principle behind MICP (see Figure 12). The general working involves bacteria (or a catalyst), which is capable of decomposing urea and breaks down urea into ammonium ions and carbonate ions. The carbonate ions react with calcium ions from calcium chloride in the solution, leading to the formation of calcium carbonate precipitation. The carbonate precipitation acts as a "bridge" to connect clay brick particles.

However, the generated white calcium carbonate precipitation may not adhere to the brick particles. If not, it cannot serve as a "bridge". Therefore, guiding the calcium carbonate precipitation onto clay brick particles is a research question needs to be further explored. In my experiment, the biomaterial has some fragmented clay brick powder particles on its surface. One potential physical solution to improve this issue is applying pressure to the materials during the chemical reaction.

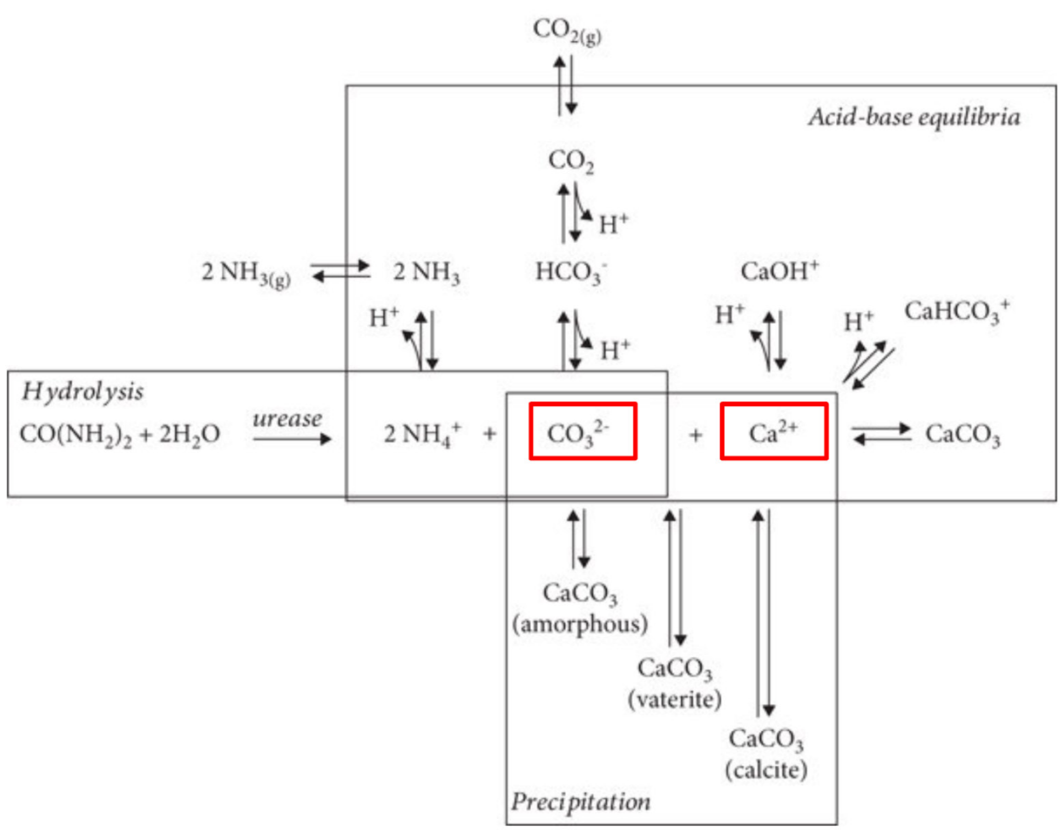


Figure 12. Chemical principles of MICP

Chemicals Recipe

Biomimetic Recipe - Quicklime (Calcium Oxide)

The principle of MICP mentioned earlier involves the generation of calcium carbonate precipitation between clay brick particles. There are various methods to produce calcium carbonate, and one of them is using quicklime (calcium oxide). Quicklime reacts with water in the environment to form calcium hydroxide. And then calcium hydroxide absorbs carbon dioxide from the surroundings to form calcium carbonate precipitation. Figure 13 shows this chemical equation.

Through testing, this method does indeed cause clay brick particles to adhere together (see figure 14). However, a challenge is that the material becomes very brittle, which means it can be easily broken. Further research is needed to explore the addition of potential polymers such as glycerol to alter its characteristics.

$$\mathrm{CaO} + \mathrm{H_2O} \longrightarrow \mathrm{Ca(OH)_2}$$

$$\mathrm{Ca(OH)_2} + \mathrm{CO_2} \longrightarrow \mathrm{CaCO_3}\downarrow + \mathrm{H_2O}$$

Figure 13. The chemical reaction equation of calcium oxide to calcium carbonate

Figure 14. Prototype image of using quicklime recipe

Through chemical reaction inference, CaO is believed to have the ability to absorb carbon dioxide from the environment.

However, to increase credibility, I conducted experiments using a carbon dioxide sensor. I let the carbon dioxide sensor run for 19 minutes for calibration and preheating. I placed 1g of CaO (quicklime) in a sealed 140mm(5.5 in) cubic container. After 3 hours, the carbon dioxide content changed from 429 PPM to 400 PPM, which confirmed the material's significant potential in addressing the climate crisis. The test process can be seen at Figure 15.

$$1g\ CaO = 29\ PPM$$

Figure 15. A: Initial carbon dioxide content 429 PPM. B: Carbon dioxide content after three hours: 400 PPM. C: Carbon dioxide content after three days: 400 PPM. Through comparison of the images, it can also be observed that the color of the samples changes over time. Upon closer examination of the image B, a transparent film can be seen forming on the surface of the sample.

Protein Recipe

Proteins are long chains whose links are amino acids. An amino acid is a small molecule composed of an asymmetric carbon, linked to a carboxyl function (COOH), an amine function (NH2), a hydrogen (H), and a group (R). This side chain, R, identifies each amino acid.

There are in total around twenty distinct amino acids, making up all living proteins. These amino acids have very different characteristics: some are polar, others carry electrical charges, and others on the contrary are hydrophobic. An average-sized protein is made up of about 200 amino acids. There are two main types of proteins: profibrous proteins (collagen) and globular proteins (casein). The latter adopts a particular spatial configuration: their long chain folds back on itself, taking a very specific shape. The functionality of a protein, including its surface characteristics, is determined by the sequence of amino acids and how they are organized in space.

Proteins interact strongly with clay tiles. The hydrophilic parts adsorb on the clay tile particles covered with thin layers of water molecules, while the hydrophobic parts remain outside the material and therefore in contact with the air, forming a sort of surface film which repels water.

The visual visualization generated by chatGPT is shown in Figure 16.

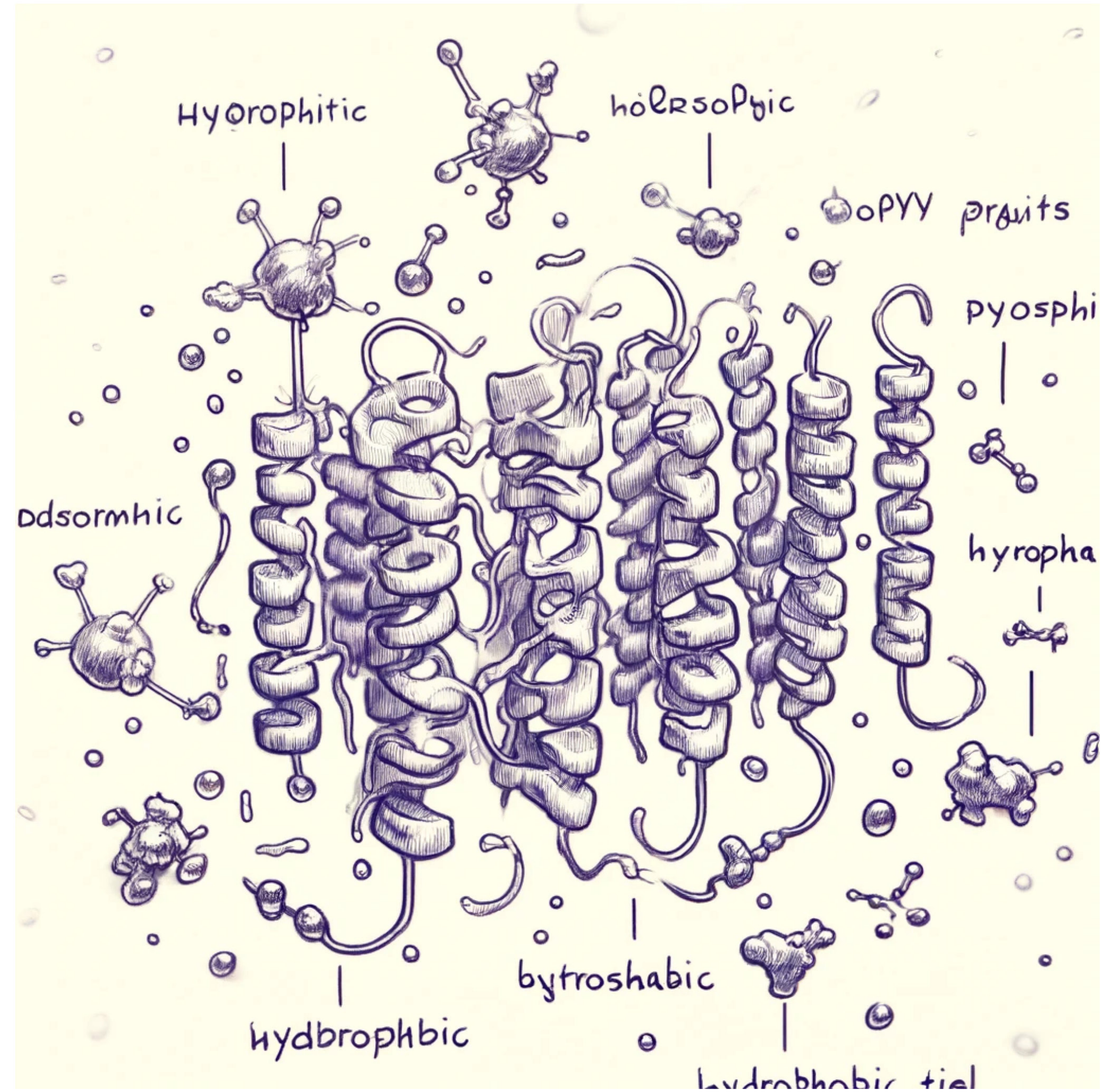


Figure 16. Principles of Proteins binding brick particles

Protein Recipe
Bio Recipe - Casein

Casein is a protein found in milk, serving as an emulsifier that produces highly stable emulsions of the oil-in-water type. It is sourced from various origins including milk, 0% fat cottage cheese, and powdered casein formulations. Casein molecules naturally form into minuscule spherical aggregates. The production of casein-based adhesives necessitates disrupting these structures to disperse the casein molecules. This process involves the milk or white cheese transitioning from opaque to translucent. Certain formulations employ potent bases like ammonia, ammonium carbonate, or borax to facilitate this dispersion.

On a molecular scale, casein molecules are significantly smaller than the casein aggregates. Upon exposure to substances like ammonia, these molecules acquire a partial negative charge. Despite this, they maintain hydrophobic (water-repelling) characteristics in specific regions, making them amphiphilic - capable of interacting with both water and hydrophobic substances or materials. The introduction of a negative charge influences their behavior under varying pH levels and ionic strengths, leading to electrostatic attractions or repulsions. Consequently, casein's interaction with clays can either neutralize charges, acting as a dispersant, or effectively bind clay particles together, functioning as an adhesive.

From Figure 17, it is more visually apparent to see the role of casein: wrapping around the brick particles. However, due to the presence of cracks in the casein, the binding may not very effective in the cracked areas, thereby reducing the strength of the bio-material to some extent.

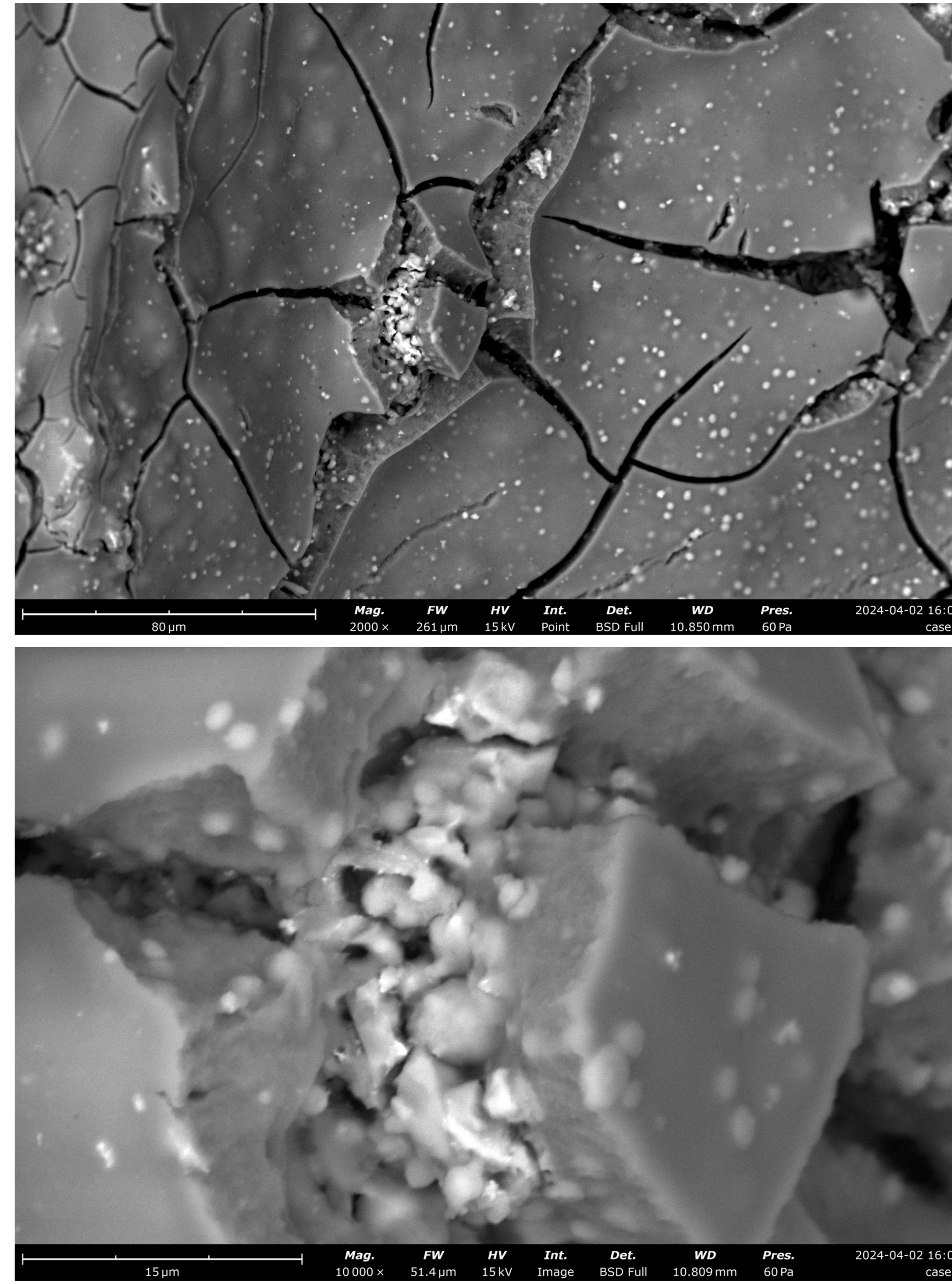


Figure 17. SEM images. Top) Magnification 2000 times. Bottom) Magnification 10000 times.

Others Recipe

Natural resins are complex mixtures of organic compounds, primarily consisting of terpenes and their oxygenated derivatives. These are built from isoprene units (C_5H_8) linked together in various configurations. Terpenes are hydrocarbons, while terpenoids have additional functional groups, such as hydroxyl (-OH), carboxyl (-COOH), and ethers (R-O-R'), which can interact with other molecules through hydrogen bonding, Van der Waals forces, and other types of chemical bonds. Upon curing or drying, natural resins undergo chemical reactions that lead to the cross-linking of their molecular chains. This process transforms the resin from a viscous liquid to a solid state, providing the binding force necessary for its role as biocement. Furthermore, the chemical structure of natural resins determines their interaction with water. Some resins are inherently hydrophobic, repelling water and providing water-resistant properties to the bio-cement. Others may contain hydrophilic functional groups, allowing for some degree of moisture absorption without compromising the structural integrity of the biocement.

A commonly used natural resin is Pine Resin (Rosin). However, due to certain limitations, my experiments utilized Epoxy Resin, a versatile polymer material extensively employed in a variety of applications, from arts and crafts to heavy-duty industrial coatings. It falls under the category of chemicals rather than natural resins. However, from a macroscopic perspective, both share the characteristic of transitioning from a viscous liquid to a solid state. Figure 18 is an Epoxy Resin test. The color will be yellowish if nature resin is used.

Figure 18. “Bio” recipe - Resin

Recipe							
	Brick+Alginate **Polysaccharides**	Brick+Sugar **Polysaccharides**	Brick+CaO **Chemicals**	Brick+Urine **Proteins**	Brick+Casein **Proteins**	Brick+Clay **Other**	Brick+Resin **Other**
Manufacture Method	Cast, 3D Print	Cast, 3D Print	Cast	Cast	Cast	Cast, 3D Print	Cast
Curing Time	Fast	Fast	Low	Very Low	Fast	Fast	Fast
Water Resistant	Y (Mix with calcium ions)	N	Y	Y	Y	N. After fire:Y	Y
Contribution	Reduce Landfill	Reduce Landfill	Reduce Landfill Reduce Carbon	Reduce Landfill & biological waste	Reduce Landfill	Reduce Landfill	Reduce Landfill

Figure 19. Conclusion diagram of material research.

Chapter Three

Material Research

Production Methods Exploration

Different recipes require different production methods. For example, the recipe of CaO cannot be used with 3D printing technology due to the time it takes to solidify. The principles behind the recipes of Urea and Resin are the same. However, they can be produced using the casting method.

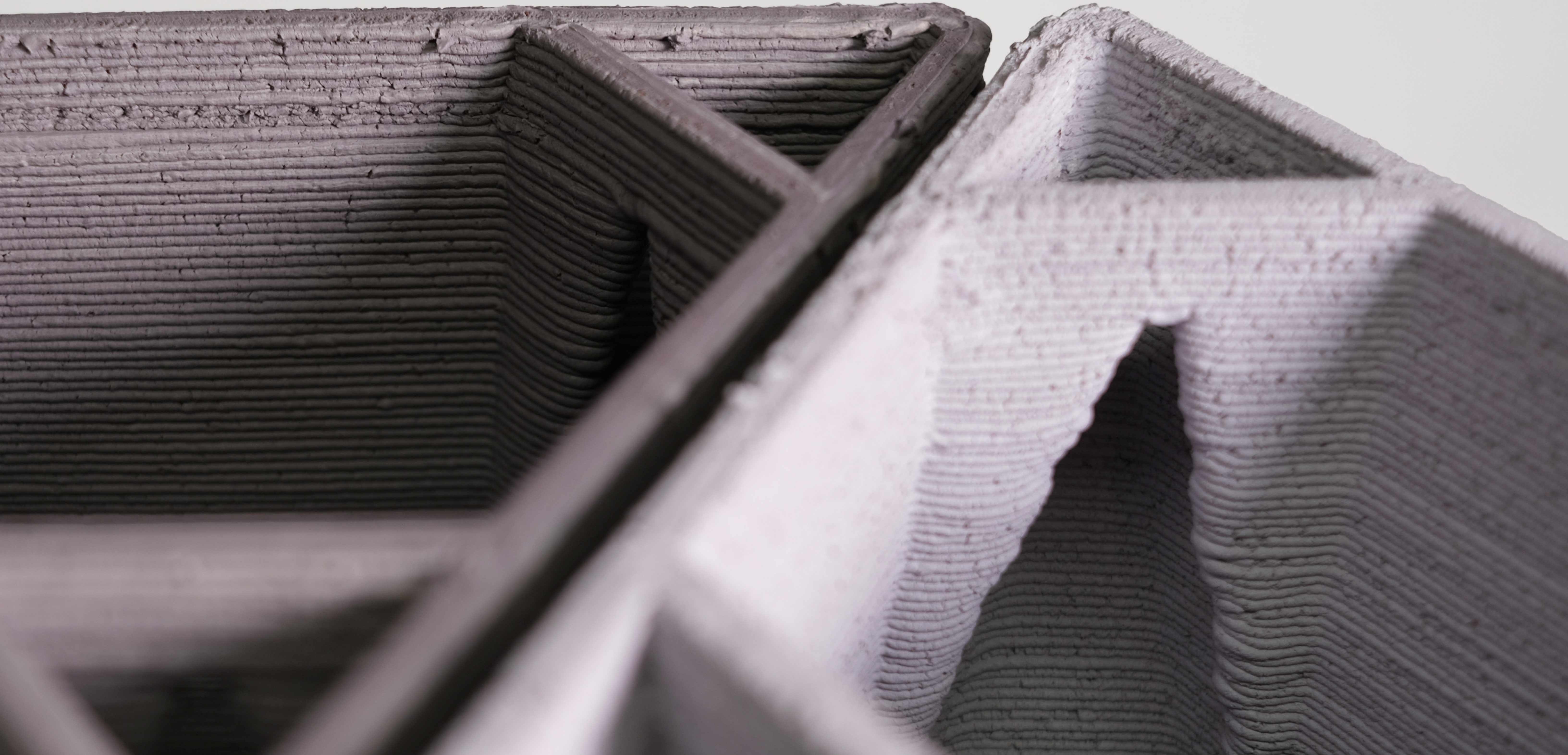
Casein recipe is a bit tricky. By using different amounts of casein, you can adjust the speed of solidification, and its solidification rate is relatively fast. So, this recipe may be suitable for production using 3D printing. Due to time constraints and equipment limitations, I have not conducted testing. The recipes categorized under the Casting category are depicted in Figure 20.

I choose 3D printing as the current practice because its unparalleled precision and the ability to customize products without the need for new tools or molds, as well as it minimizes waste through precise material usage and reduces the amount of raw material needed. More importantly, digital files for 3D printing can be shared globally, allowing for local production that adapts to specific regional needs and reduces the carbon footprint associated with transportation. This aspect supports decentralized manufacturing, which can empower communities and promote local economies. The recipes categorized under the 3D printing category, along with their respective prototypes, are shown in Figure 21, 22, 23.

Figure 20. Casting Category

25.8% brick and 74.2% blue porcelain (Collet Clays Corp.). The different colors of the models on the left and right are due to their different drying times, with the model on the right having a longer drying time.

Figure 21. 3D printing category - Brick and Clay (porcelain)



In this experiment, I added 20% clay to increase the plasticity of the mixture.

Figure 22. 3D printing category - Brick, Sugar and Clay

100% brick. Its characteristics are completely different from clay. It lacks plasticity and is not suitable to print for the complex modeling of 3D models.

Figure 23. 3D printing category - Brick and Alginate

Chapter Four

Product Innovation

Designing products that incorporate ceramic waste requires a deep understanding of both the material's properties and the needs of potential users. Products that are durable, functional, and aesthetically pleasing, yet also sustainable, are more likely to be embraced by the market. The key to success lies in creating products that do not compromise on quality or functionality for the sake of sustainability. By seamlessly integrating ceramic waste into products that people desire for their utility and beauty, designers can significantly contribute to the broader acceptance and application of these sustainable practices.

Porcelain tile is a type of interior building material commonly used in bathrooms and kitchens. It is highly valued for its moisture resistance, and its hard, dense nature offers exceptional durability and stain resistance, facilitating low maintenance. Its vast range of designs, textures, and colors, contributes to both the aesthetic and practical aspects of architectural spaces. Electric light is also a kind of interior building material, a set of evolving compositional practices, and a host of occupational strategies that produced new places to live, work, and play. It is an instrument of spatial invention as well as a decisive condition for nighttime inhabitation (Sandy I., 2019). Therefore, combine art and design with waste to make useful lamps that are not only aesthetically appealing but also remind humans to protect their planet and brighten their families. The creation of this lamp not only diverts still-usable items from landfills but also reduces the amount of energy required in the production process and the need for clay extraction.

Chapter Four

Product Innovation

Modular Lamp Design

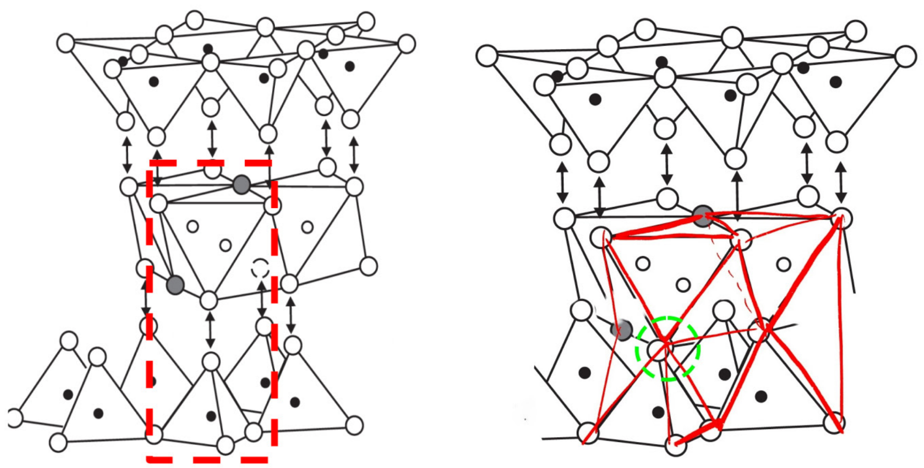


Figure 24. Left: Three-dimensional assembly of tetrahedral and octahedral sheets and formation of the 1:1 layer and the 2:1 layer. Large white circles are oxygens, large grey circles are hydroxyls, small white circles are octahedral ions and small black circles are tetrahedral ions. The image is from G.E. Christidis (2011). Right: Author's sketch

The design inspiration for the Modular Lamp comes from the molecular behavior of clay, as shown in Figure 24, which offers the possibility of stacking, arranging, or disassembling the elements as desired. Its structure, as can be seen in the left image of Figure 24, is roughly composed of an octahedron on top and a tetrahedron at the bottom, sharing a white circle in the middle.

During the design process of the lamp, it was considered that if the connection point between the upper and lower parts was a sharp angle (The green dotted circle in the image to the right of Figure 24), it would lead to easy breakage due to the lesser material at the joint. Therefore, in the final design, the connection point was changed to a line segment, appropriately increasing the distance of the seam to strengthen the product's durability. Additionally, to make the product more aesthetically pleasing, the entire product was designed to be symmetrical both vertically and horizontally, with the opening being an equilateral triangle.

For modular products, it is important to consider the way to connect each other. Based on this, I designed triangular containers at the three corners of the model's top and bottom openings, as shown in Figure 25. This design not only increases the contact area when placed vertically but also allows for the insertion of Vertical Connectors to reinforce the connection in the vertical direction to some extent. As for the horizontal connection, the U-shaped Horizontal Connector is designed to function like a clamp, securing each module tightly in the horizontal direction.

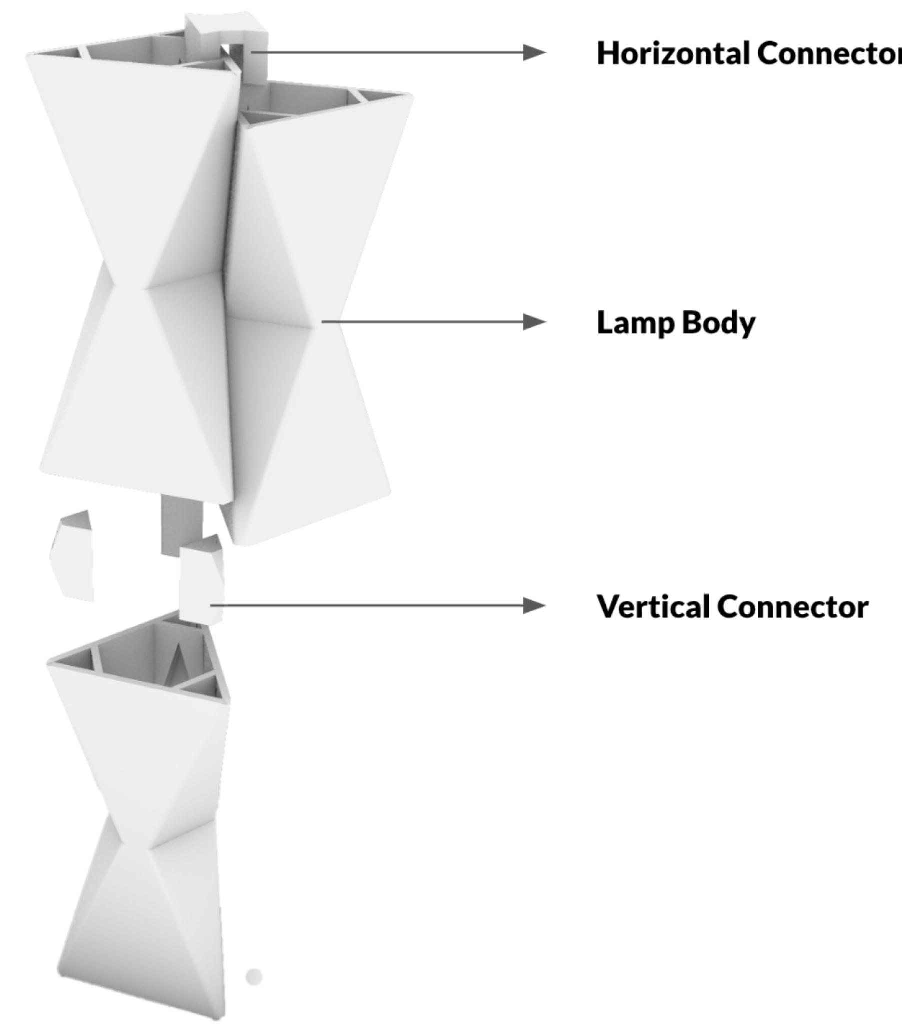


Figure 25. The connection of the modular lamp

Figure 26 showcases a series of model explorations using Rhino 3D software.

Section A depicts models that are arranged to visualize clay and molecular structures, inferred from the clay's molecular composition. From the top view of the models, it's evident that one large model consists of six smaller ones.

Section B involves a series of iterations refining the model details after establishing the basic structure. I adjusted the proportions of length, width, and height and using PLA material to 3D print physical models to compare their appearances. This process led to the selection of a model with optimal visual proportions as the final iteration.

Section C explores the concept of the half-sized model, I didn't choose this as I think they are relatively simple, although they offered more arrangement possibilities than full-sized ones.

Section D involves stacking the models on a vertical plane to observe the geometric patterns from different angles.

Section E involves stacking on a horizontal plane, creating different textures and voids through varied arrangements.

Section F depicts initial explorations of connecting horizontal and vertical planes, different from those shown in Figure 25. This method was not chosen as it significantly altered the original geometric surface textures.

The green circles on the right indicate the initial connection of faces at points, while the models within the green circles on the left demonstrate faces connected by a straight line, as mentioned earlier.

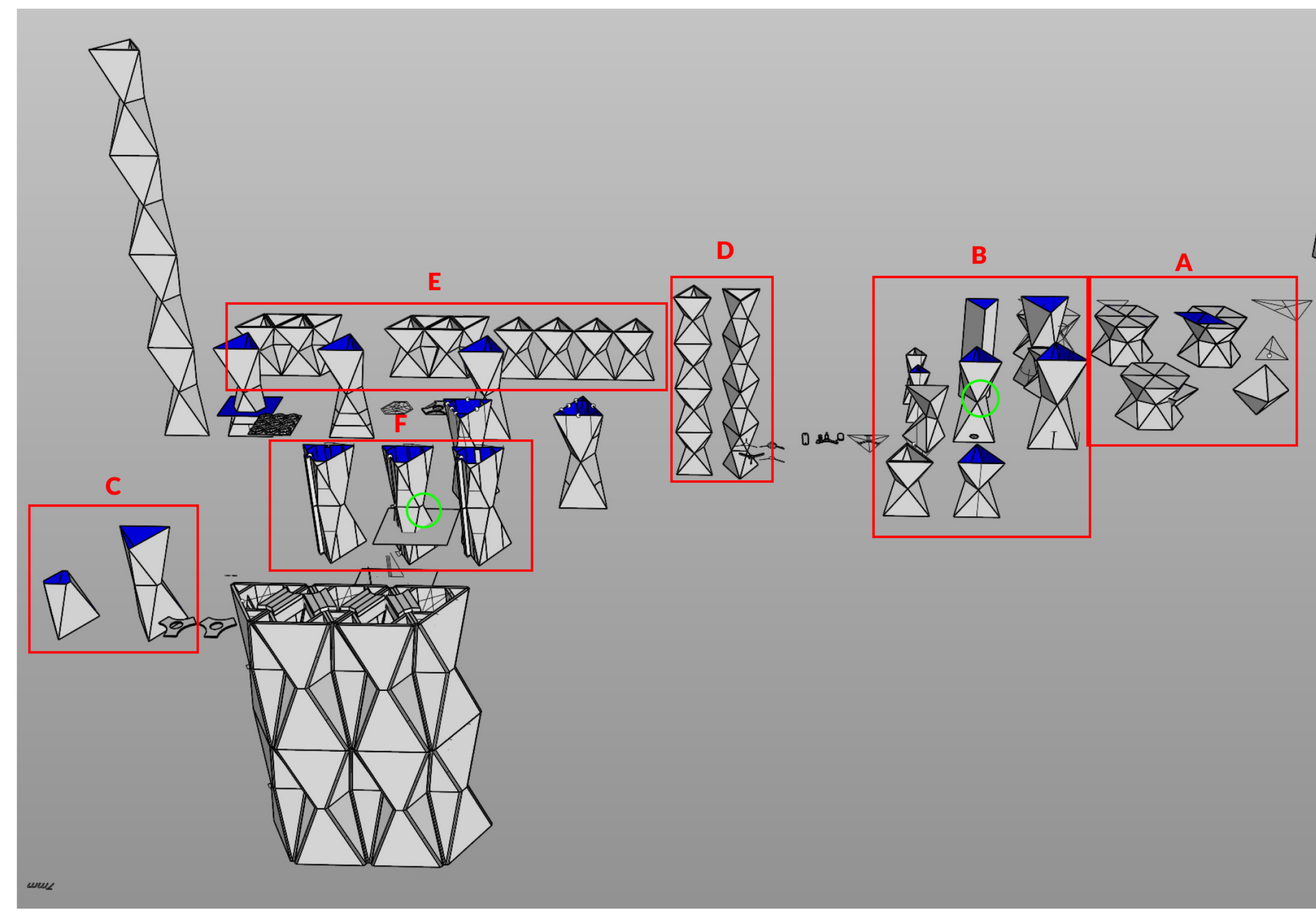


Figure 26. Design Process

Chapter Four

Product Innovation

Lamp Production

The production of the lamp explores new opportunities for craftsmanship using digital printing technology. Compared to casting, this cutting-edge technology not only allows for personalized customization but also leverages the properties of clay and Earth's gravity to create unexpectedly shaped details. I also explored creating some iterations on the original model's surface. The prototypes are shown in Figure 27, 28, 29, 30. Furthermore, I attempted to print models made from different types of porcelain clay and various proportions of porcelain clay mixed with tile dust. The parameters and characteristics of these different compositions will be detailed in the next section.

Figure 27. On the surfaces of the initial model, some triangular holes were added to guide the direction of light. However, in practice, human intervention is required as additional support during printing because the extrusion of the mixture is not very smooth and fluid as pure clay.

The model is unfired and made of porcelain paper clay and brick dust.

Figure 28. The initial model. Each surface consists of clean geometric shapes.

The model is unfired and made of blue porcelain and brick dust.

Figure 29. The initial two models stack horizontally. These two models are made of the same materials. However, the color looks different. It is because the drying time is different.

The model is unfired and made of blue porcelain clay.

Figure 30. The initial model. However, during printing, there were inconsistencies on the upper part, resulting in the texture depicted in the image. It is fired and made of Porcelain Moist Clay and brick dust.

Chapter Four

Product Innovation

Results and Discussion

The clay I purchased came with 11 lbs, which, when combined with brick, allowed for the printing of three models. Therefore, I printed three models for each type of clay for comparison. The specific types of clay used, along with different mixtures of waste, are illustrated in Figure 31. It can be clearly seen that their shrinkage rates differ. It may due to factors such as uneven mixing of clay and brick, variations in the extrusion state of the printer, and differences in placement during firing on the cone.

The feel of different clays actually varies. Porcelain Paper Clay and Porcelain Moist Clay have a higher moisture content, feeling creamy to the touch. Black Porcelain has a softer texture, and I found it easier to mix with waste compared to other types of clay. Hence, I achieved a 1:1 ratio of waste to clay. The initial intention of the project is to use minimal clay while retaining the plastic properties of the mixture for 3D printing lamps. However, due to time constraints, I did not attempt higher ratios, as I fear that the mixture might not be plastic enough during printing and would result in intermittent extrusion. When I tried to print at a 50% waste ratio (the black porcelain mix), I had to adjust the extrusion power of the 3D PlotterBot Pro 10 to 140% to ensure smooth extrusion without interruptions.

Additionally, as seen in Figure 32, the shape of Black Porcelain changed a lot. However, the product information provided by the seller suggested a firing temperature of Cone 6-7. Yet, firing at Cone 6 caused deformation of the model, which indicates that the addition of a certain amount of tile dust can lower the firing temperature of the clay. Thus, the conclusion can be drawn that adding tile dust to clay has the potential to lower the firing temperature and conserve energy.

Blue Porcelain total shrinkage: 15.6%

Porcelain Paper Clay total shrinkage: 15.8%

Black Porcelain total shrinkage: 15.7%

Temperature Range	Cone 4 - 6
Grog	No
Color In Oxidation	White
Color In Reduction	Blue White
Shrinkage	c/6/ox. 14.50%
Absorption	c/6/ox. 0.00%

Porcelain Moist Clay total shrinkage: 14.5%

Clay Type	Waste Percentage	Shrinkage Rates (Cone 6)
Blue Porcelain Collet Clays Corp. $2.69/lb	25.8% waste	28.8cm 29.6cm 29.5cm 16.0% 13.7% 14.0%
Porcelain Paper Clay Collet Clays Corp. $2.29/lb	27.4% waste	27.5cm 27.9cm 19.8% 18.7%
Black Porcelain Collet Clays Corp. $2.22/lb	50% waste	Failed Failed
Porcelain Moist Clay Sheffield Pottery Inc. $1.55/lb	37.5% waste	31.8cm 30.2cm 7.3% 12.0%
Porcelain Moist Clay Sheffield Pottery Inc. $1.55/lb	0% waste	28.6cm 28.8cm 28.9cm 16.6% 16.0% 15.7%

Figure 31. Information about the clay used for 3D printing, along with the results of different waste content tests and a comparison of actual shrinkage, can be provided.

Figure 32. Failed Black Porcelain model.

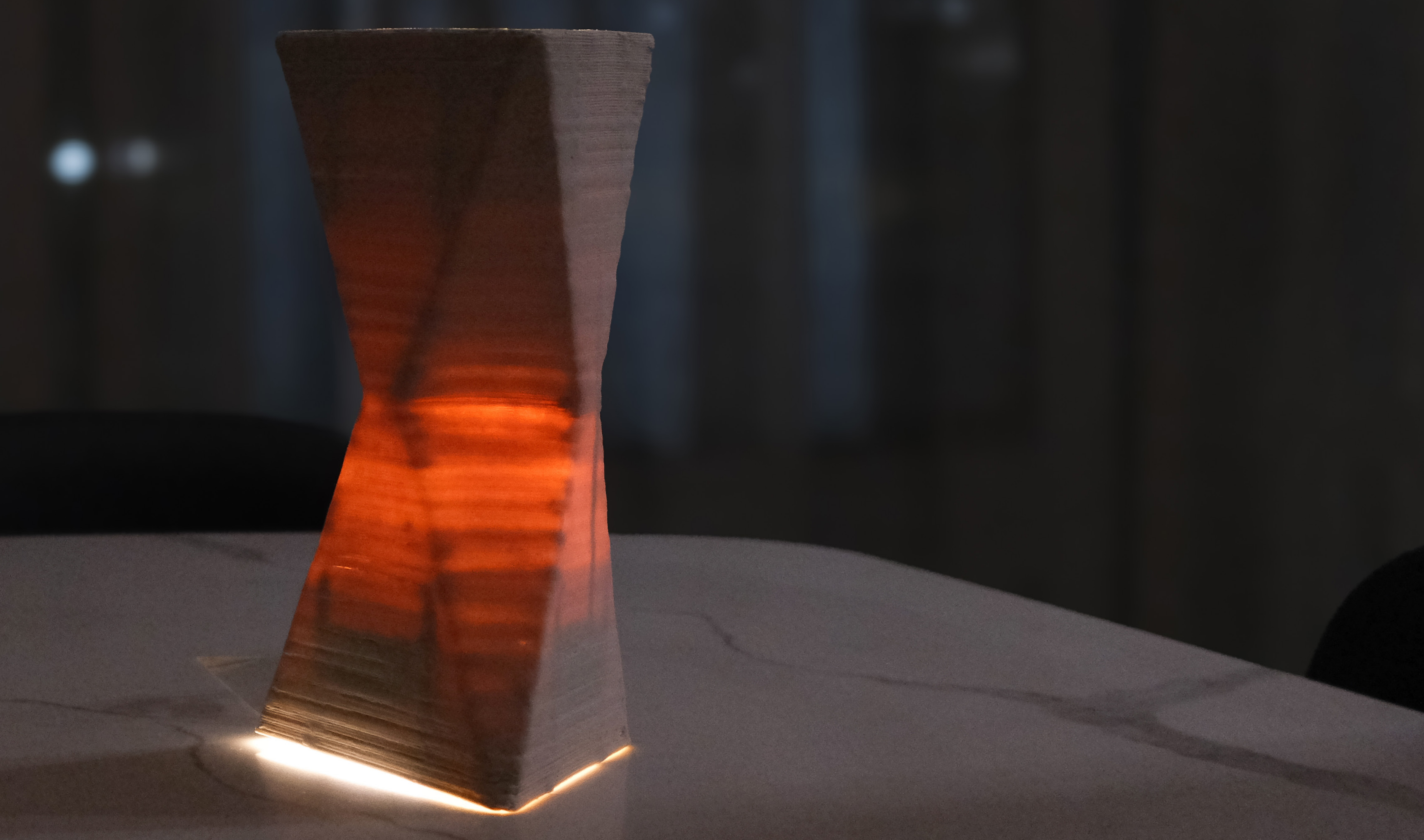


Figure 33. Image of the Pure Porcelain Moist Clay model after firing, with no waste present. Its surface has been preliminarily polished and appears translucent.

Figure 34. Blue Porcelain after firing

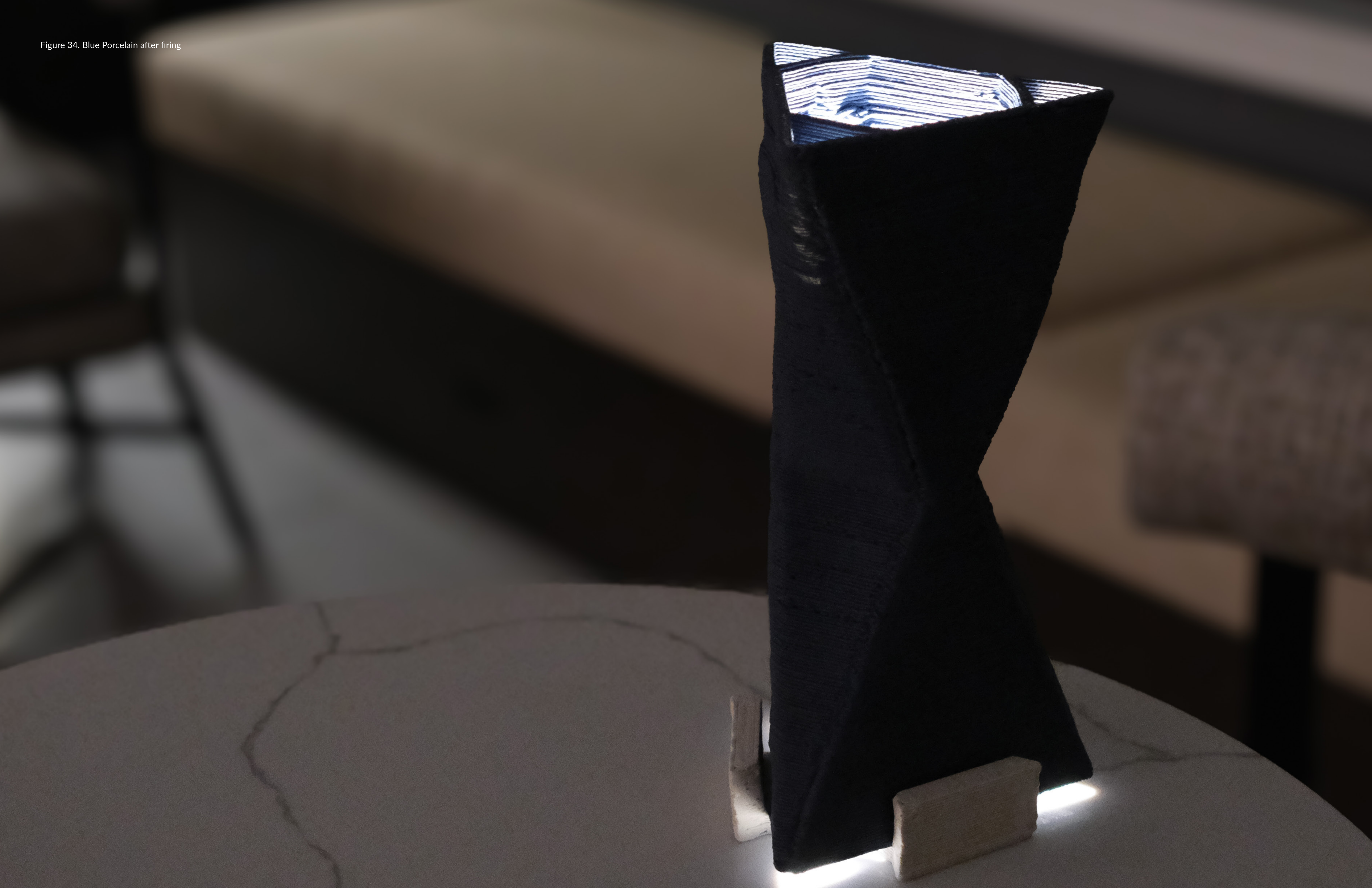


Figure 35. The lamp is hanging from the ceiling.

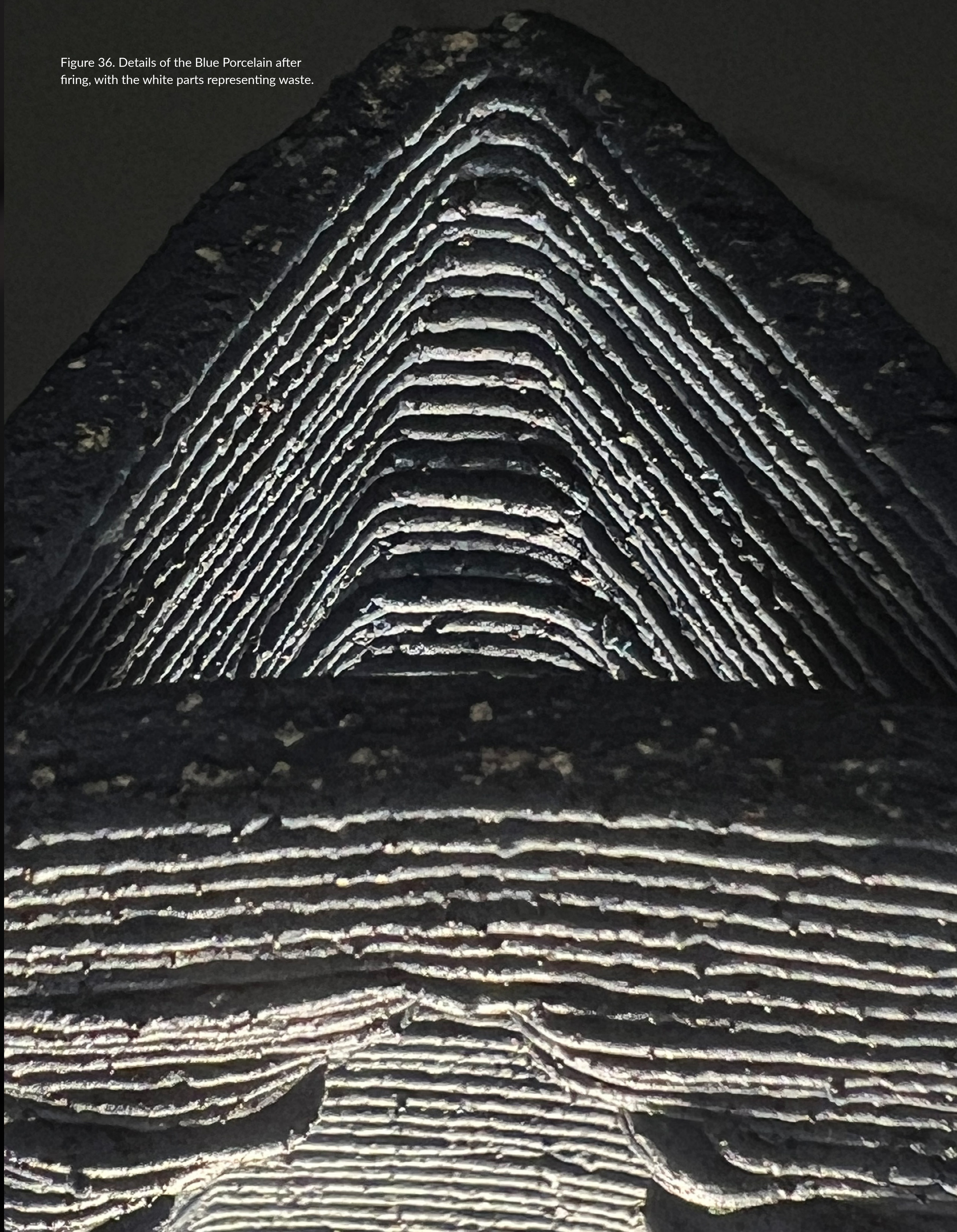


Figure 36. Details of the Blue Porcelain after firing, with the white parts representing waste.

Figure 37. Close-up detail image. After firing, the tile dust changes from brown-yellow to black.

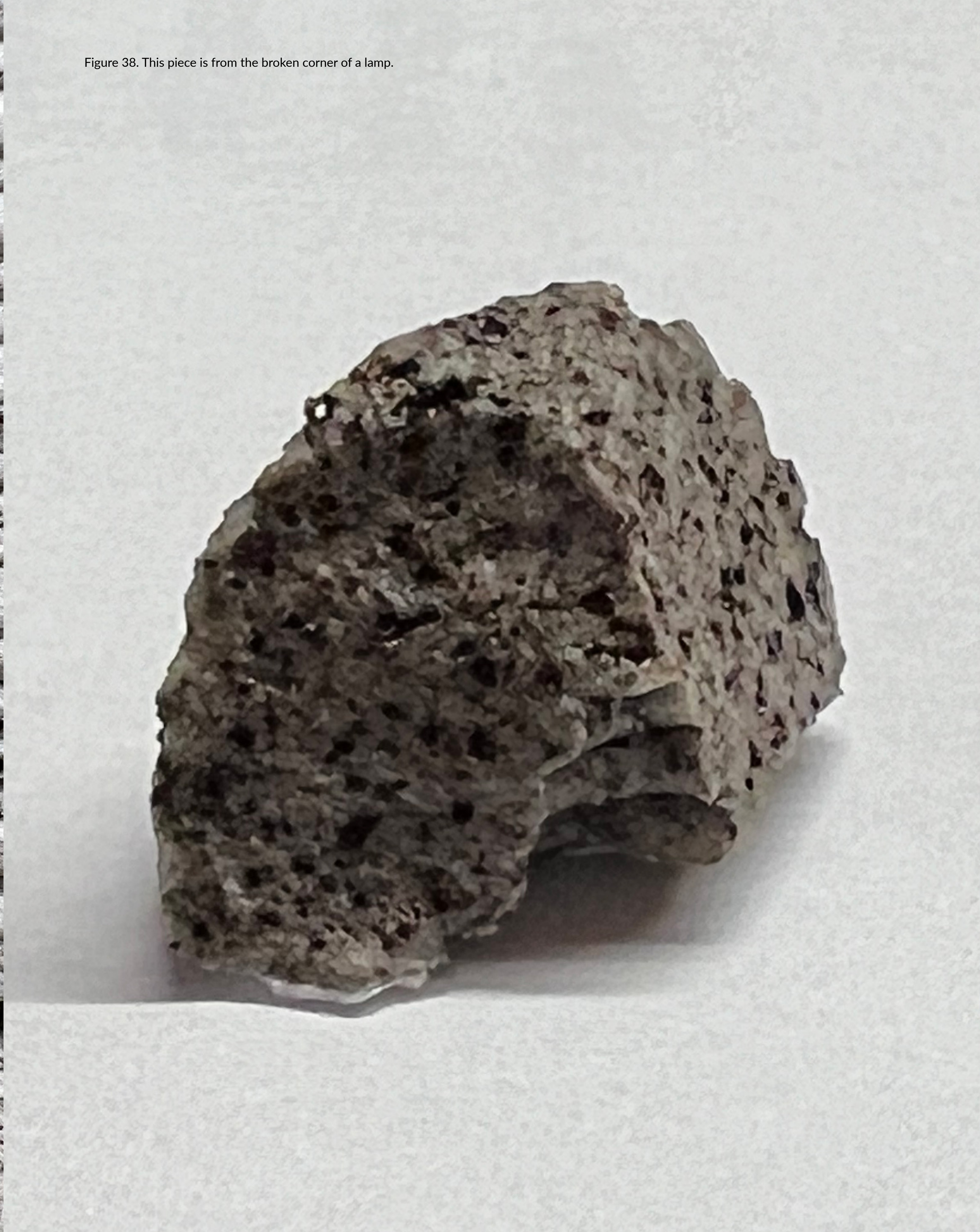
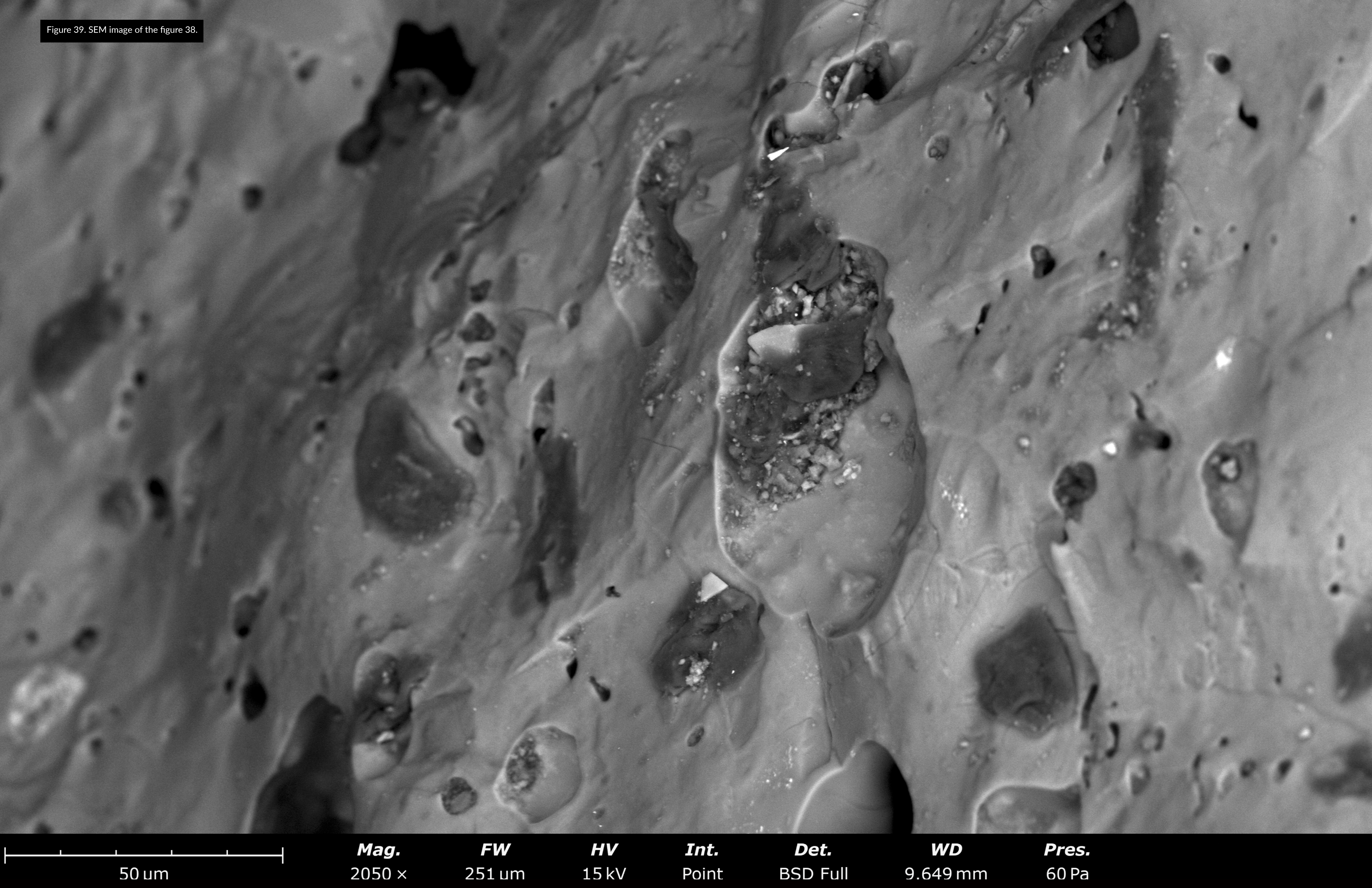


Figure 38. This piece is from the broken corner of a lamp.

Figure 39. SEM image of the figure 38.



Chapter Five

Design Impact

Yield

A single clay tile weighs approximately 2 kg. The conversion rate of grinding clay tiles into particles with a grain size of less than 0.1 mm is only 50%. A lamp consists of 50% clay and 50% waste, so its weight is approximately 2 kg. If the waste comes from clay tile manufacturing dust, there is no need to use a machine to crush the tiles.

In 2018 (the latest available data), there were 10.8 million tons of brick and clay tile waste that couldn't be recycled. However, there are 84.33 million households in the United States. If every household in the United States adopts this lamp, it could reduce landfill area by 1.4 acres, equivalent to 1.4 soccer fields. Additionally, the energy saved in producing the lamp could supply the annual electricity consumption of 1273 households. (The lower firing temperature can save 10%* of energy)

*The source of the 10% energy saving comes from the article by Amin, Sh K., et al. titled "Recycling of ceramic dust waste in ceramic tiles manufacture," published in the proceedings of the 6th IconSWM 2016 conference, which is available in the book "Waste Management and Resource Efficiency" by Springer Singapore, 2019.

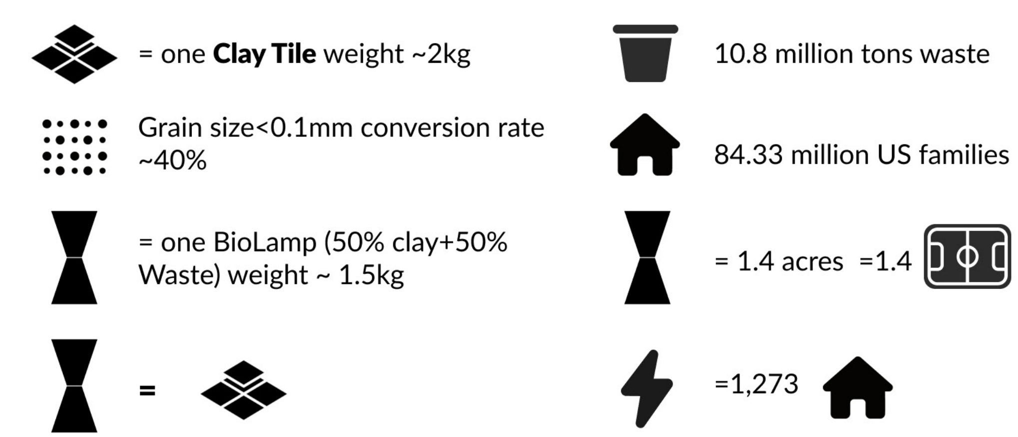


Figure 40. Yield

Chapter Five

Design Impact

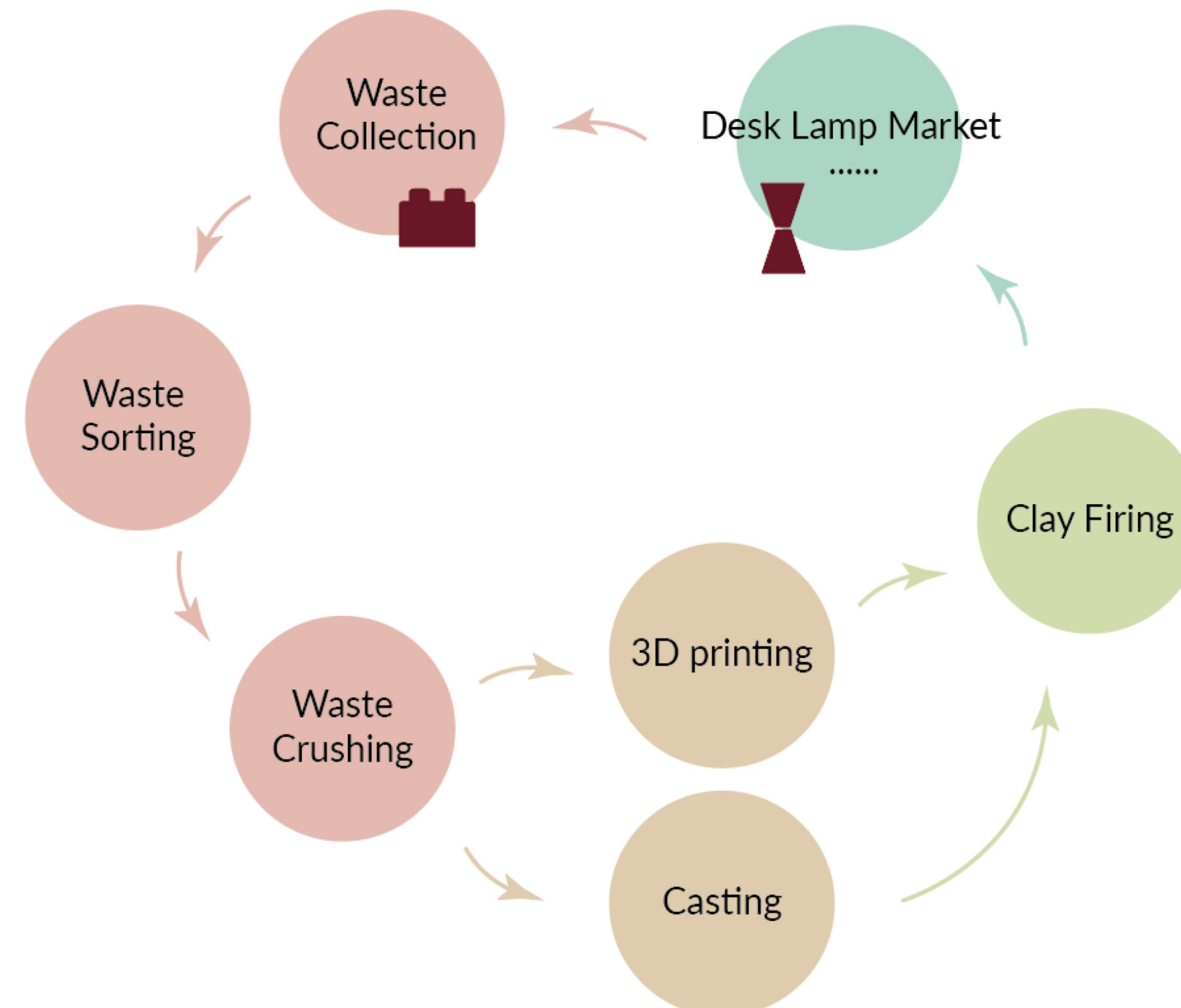
Brick As Currency

As previously demonstrated by the yield, a lamp represents a clay tile recycled from a landfill. A clay tile costs only $1, while a fundamentally similar lamp costs $200. Through the power of design, not only can the value of similar goods be changed, but it can also generate a force to improve the environment.

The concept of using bricks as currency presents a visionary approach to business that integrates environmental sustainability with economic innovation. Here, waste bricks are not merely recycled; they are transformed into a standardized unit of economic value. This novel system quantifies the value of waste, turning every salvaged brick into a tangible asset that can be traded, used for purchases, or leveraged as collateral.

In this model, bricks act as a sustainable currency that encourages recycling and reduces environmental impact. Businesses can earn bricks by contributing to waste reduction efforts, such as salvaging materials from demolition sites or participating in recycling programs. These bricks can then be used to pay for goods, services, or even taxes, creating a circular economy that values sustainability. Specially, starting from a waste collection company, the number of wastes they obtain is calculated by dividing the weight of the recycled bricks and clay tiles by two. In this supply chain, all transactions are carried out using a virtual currency called "bricks". If merchants wish to convert their bricks into cash can do so at a rate of one brick per one US dollar, similar to credit card points system rules. Each final lamp which is made of wastes sold on the market is financially equivalent to earning 180 bricks. The market acts like a bank, where all companies involved in the early stages of lamp production can exchange their brick currency for cash.

Ultimately, this approach not only redefines the intrinsic value of what was once considered waste but also fosters a marketplace where environmental responsibility enhances economic opportunity, driving a shift towards more sustainable business practices.



Waste refers to the brick and clay tiles from the construction and demolition.

1 brick currency = 1 US Dollars =1/180 Lamp

Figure 41. Stakeholders involved in the Brick Currency.

Chapter Six

Conclusion

My solution which transforms these waste materials into functional, aesthetically pleasing printed lamps, directly addresses the environmental concerns associated with waste disposal while also promoting sustainability and reducing the demand for new raw materials. This approach not only benefits the environment but also provides an innovative solution for homeowners, designers, and anyone interested in sustainable living and design, offering them unique products that tell a story of transformation and sustainability.

These lamps are not just about recycling. They are changing perspectives on waste and sustainability by providing tangible products that illuminate the importance of environmental stewardship and redefining the value chain for construction materials. By turning waste into a desirable product, it challenges the status quo of both the waste management and home decor industries. This solution could catalyze broader positive impacts by setting a precedent for circular economy practices in sectors notorious for their environmental footprints. It encourages manufacturers, designers, and consumers to rethink the lifecycle of building materials, promoting a shift towards more sustainable consumption and production patterns. Moreover, this approach has the potential to change the market landscape by introducing a new category of eco-friendly interior design products, which could spur increased demand for recycled materials, encouraging other industries to explore similar upcycling initiatives. Ultimately, it not only addresses the immediate issue of waste but also contributes to a larger cultural and economic shift towards sustainability.

My thesis has benefits in terms of social equity and inclusion as well, as shown on Figure 42. It not only has the potential to reduce greenhouse gases and the volume of construction and demolition waste, but by sharing some biomaterial recipes, it can enhance the accessibility of education and decentralize the topic of sustainable development.

Carbon Reduction

One material recipe can absorb environmental carbon dioxide, contributing to the reduction of the greenhouse effect.

Waste Reduction

It not only addresses local waste management issues but also contributes to global efforts in reducing construction waste.

Figure 42. Thesis on Social Equity & Inclusion (Continue on the next page.)

Educational Accessibility

It is particularly beneficial for those who may not have formal education in sustainability or access to specialized facilities.

Democratizing Sustainability

By being community-driven, whether individuals purchase products or DIY their own through given recipes.

Figure 42. Thesis on Social Equity & Inclusion (Continue on the previous page.)

Chapter Seven

Limitations and Future Work

The high-end lamp made of brick dust and porcelain is merely one of the further in-depth tests of the “clay + brick” recipe from Chapter Two's material research. However, the types of clay are not limited to just porcelain; other materials like earthenware are also viable. Additionally, the ratio of clay to waste currently stands at 1:1, leaving ample room to increase the proportion of waste and reduce the use of new clay. The next step in testing will involve using 80% waste and only 20% clay to ensure the plasticity of the mixture.

As for other materials, alginate and sugar, as shown in Figures 23 and 24, have the potential for 3D printing using 100% waste. More shapes and printing models will require further testing.

Casein is a recipe with potential for 3D printing. Due to time constraints and limitations of the printer, I only extrude brick dust and casein from the printer, as sown in Figure 43. Future plans involve testing the 3D printing of casein mixed with 100% waste.

Other promising recipes such as urea and calcium oxide were only tested on samples due to time and material science knowledge constraints. Future plans include studying the strength of reinforced materials and using PLA material for 3D printing molds for casting.

Figure 43. Brick+Casein recipe is extruded from the 3D printer.

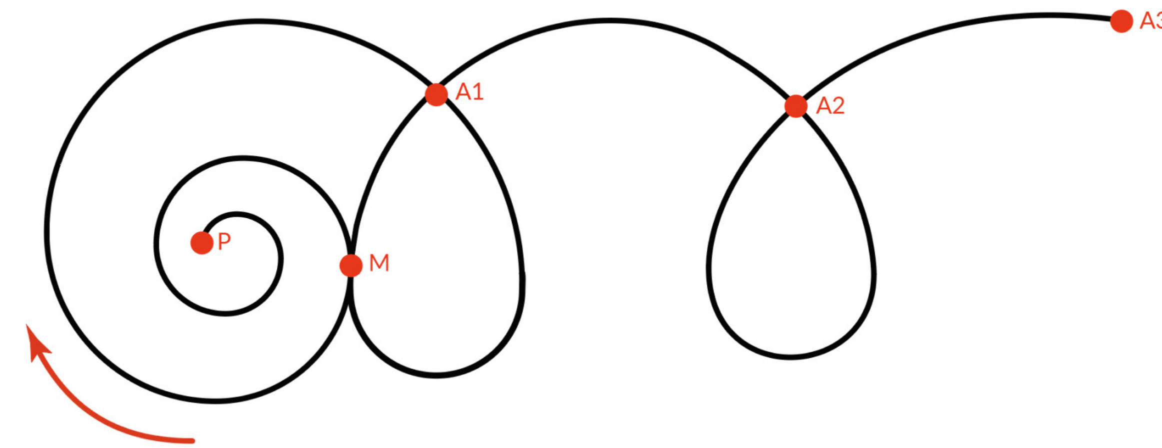


Figure 44. Spiral Design Theory.
P for Problem, M for Method, A1 for Application1, A2 for Application2, A3 for Application3.

The Spiral Design Theory depicted in Figure 44 is a design methodology derived from the conclusions drawn in my thesis. The starting point of the spiral design theory is P, which stands for Problem. After determining P, then move to point M, which represents Method to intervene the problem. This Method can be a new material, technology, or service. A1 is the first application using that method. The distance from point M to A1 is relatively long as the method need to be tested to ensure that the design outcome A1 can interact with the problem well and also be the best choice according to the methodology.   After reaching A1, it is necessary to iterate, considering user/business feedback and whether the method is appropriate. Then come to A2, the second application after iteration. It can be a completely new direction or an optimized application based on A1. The iteration continues for A2, and at this point, there is no need to reconsider methods as two rounds of design outcomes have been produced. Iterating on A2 will lead to the application of A3, and the process continues iteratively to produce A4, A5, and so on.

Reflecting on my thesis, P represents the issue of brick and clay tile waste. M stands for my biocement - a new material solution to this problem. A1 represents the printed modular lamp, a method to address the waste issue using one of the biocement recipes. However, is this the most effective approach? After implementing this solution, I need to reconsider the biocement recipe. Utilizing 100% brick dust and casein for 3D printing is a feasible, slightly more challenging, yet more environmentally sustainable solution, which then becomes A2. However, due to time constraints, A2 remains to be implemented in the future.

Chapter Eight

Behind The Scene

Figure 45 depicts the final presentation setup for the Fall semester, marking the beginning of thesis research. This semester primarily focused on material research. Figure 46 showcases the major prototype development undertaken during the second semester.

Figure 47-49 shows part of the experimental process of 3D printing.

For more information about the project and its awards, please visit the website https://www.zhuyechen.com/wastes-illuminate-worlds.

Figure 45. 2023 Fall semester final crit.

Figure 46. 2024 Spring semester mid crit.

Figure 47. Failed printing of texture exploration on the model surface.

Figure 48. Early small model printing, after fire to present the ideal effect of translucent.

Figure 49. Printing with brick dust and alginate recipe. Due to inadequate control of the moisture content in the materials, the high moisture content caused the collapse of the entire model after the print.

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On the evening of December 29, 2021, at 10:20 PM, I landed at Boston Airport. This marked the beginning of my first solo international journey, which would span two and a half years. I am profoundly grateful to Dr. Adam Haar Horowitz at the MIT Media Lab for providing me with the opportunity to engage in an engineering dream collaboration. His patience significantly alleviated my concerns about using English for academic communication upon my arrival in the United States.

I extend my deepest appreciation to the Industrial Design Department for their guidance over the past 2.5 years, which has shaped me into a more mature, globally-minded innovation designer.

Special thanks to Dr. Eduardo Benamor Duarte, Dr. Tiago Torres-Campos, Lara Davis, and Soojung Ham for their invaluable advice on the direction of my thesis, material research, and product design.

I am deeply grateful to the monitors at the RISD Nature Lab for their assistance in preparing SEM samples, which provided me the opportunity to explore the microscopic world of biomaterials. Their support was instrumental in enhancing my understanding and appreciation of the intricate details of natural materials.

I am also immensely grateful to Tamara Kaplan, Michael Scimeca, and Kate Blacklock for their assistance in firing clay models. Their support was crucial in bringing my ideas to fruition.

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I see the bricks piled up in landfills not as useless waste, but as gold bricks full of potential. Let's make magic happen, shall we?

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