Incorporating Waste Fibers in Unstabilized Compressed Earth Blocks for Sustainable Construction in Ghana

A Major Qualifying Project

Submitted to the Faculty of

Worcester Polytechnic Institute

In partial fulfillment of the requirements

For the Degree of Bachelor of Science

Submitted By:

Sierra Leza

Submitted to:

Dr. Robert Krueger, Worcester Polytechnic Institute

Dr. Mustapha S. Fofana, Worcester Polytechnic Institute

Date:

5 April 2021

This report represents the work of one or more WPI undergraduate students submitted to the faculty as evidence of completion of a degree requirement. WPI routinely publishes these reports on the web without editorial or peer review.

Abstract

This project aimed to incorporate waste coconut fibers and PET plastic bottles into unstabilized compressed earth blocks (CEBs) for the purpose of reducing prevalent waste streams and supporting the use of sustainable building materials in Ghana. Informed by technical expertise and through collaboration with Ghanaian entrepreneurs and academics, two prototypes of a CEB mold were developed, as well as an experimental process of producing value-added CEBs. By collaborating with Ghanaian partners, there was an increased likelihood that the project intention and results will be more relevant and replicable for Ghanaian communities directly. This project concluded with recommendations to continue technical research and experimentation with waste-incorporated CEBs for use in Ghana.

Acknowledgements

The author would like to acknowledge the following people and organizations which helped us realize and support this project:

- Nelson Boateng, founder of Nelplast, for his expertise on incorporating plastic waste into successful pavement bricks in Ghana. His inventiveness, entrepreneurship, and insight propelled this project forward and offered social and market interest in this work.
- Dr. Fred McBagonluri, the President and Provost of Academic City College in Accra, Ghana, for meeting virtually and offering academic and technical interest in the subject of this project.
- Dr. Humphrey Danso of University of Education, Winneba, for his numerous publications on waste-incorporated building materials which helped inform this work.
- The project advisors from Worcester Polytechnic Institute, Dr. Robert Krueger and Dr. Mustapha Fofana for their support, advice, and patience throughout the duration of the project.
- Maeghan Desmarais and Michelle Fleming, who helped with the direction of the project, as well as the production and testing of the blocks.
- Worcester Polytechnic Institute for the global project opportunity, and especially the Washburn Shops laboratory managers for their equipment and advice.

Especially due to the complications from the coronavirus pandemic, this project would not have been possible without this support.

Table of Contents

Table of Figures

Table of Tables

Executive Summary

This project aimed to design earth-based building blocks that incorporate agricultural and plastic waste to further research of value-added earth construction in Ghana. Using earth as a building material is relatively common in Ghana, but earth buildings can suffer from less attractive mechanical or durability properties compared to buildings with manufactured or inorganic materials. Where earth structures lack in compressive strength or durability, they make up for by offering cultural and heritage significance, improved air quality and thermal control, reduced economic impact, and environmental benefits (Ngowi, 1997; Chandel et al., 2016; Wahid, 2012; Sunakorn & Yimprayoon, 2011). Additionally, earth building materials have been shown to perform better with the incorporation of certain additives, such as natural or synthetic waste fibers. Incorporating plastic waste and coconut coir fibers would greatly improve sustainability and reuse practices in Ghana, as well as increase the mechanical properties of earth-based building blocks, especially those without the addition of expensive and environmentally damaging stabilizers such as cement or lime.

Daily use of plastics has become globally common and environmentally problematic due to their centuries-long lifespan and low levels of reuse; plastic bottles are made with “polyethylene [PET] which forms about 70 per cent of the plastic waste in the municipal waste stream” and take around 450 years to break down (Kortei & Quansah, 2016). As little as “2% of plastic waste is recycled in Ghana”, leaving a large majority of the waste to be managed unsustainably (Adam et. al., 2020). Incineration as a waste management method, which is often used for agricultural waste such as coconut husks (Obeng et. al., 2020), leads to increased air pollution and is especially dangerous for inorganic wastes such as plastics due to chemical off-gassing. The next alternative unfortunately is often simply dumping such waste into a landfill or informally littered around the landscape (Addo et. al., 2017). Researching ways to add value to waste through incorporation into existing systems can promote innovative and useful inventions, benefit local economies, and offer massive environmental and sustainability benefits.

In order to complete this project, it was necessary to first research current earth-building practices or studies in Ghana in order to inform the creation of an earth block manufacturing process. Creating this process utilized an iterative design approach in which prototypes were designed, fabricated, and redesigned after initial uses in order to create a mold design and block

manufacturing process that was best suited to the project intentions. Because this project was intended to be done without the use of expensive equipment, materials, or chemical stabilizers, the mold was designed to be very simple to use and manufacturable outside of a formal laboratory setting. The final blocks were then dried and subjected to tests which considered physical, mechanical, and durability properties.

The results from this project are incredibly promising and show that the incorporation of waste fibers, especially PET plastic waste, significantly increase the flexural strength of the unstabilized compressed earth blocks. An increased flexural strength can insinuate a similar increase in compressive strength, which is also a very important mechanical property for building materials (Danso et. al., 2015). Due to limitations including the coronavirus pandemic, the project was unable to include co-design with Ghanaian communities and was set back in its timeline significantly. As such, the project was severely limited in its scope and ability to make enough blocks to maintain a level of statistical relevance or direct application opportunities for Ghanaian communities. While the results of this study are optimistic, more work is required to improve the statistical relevance of the research and to consider more composition variables or soil types in the scope of a future study. Ultimately, this study provides a hopeful message that further research into waste-incorporated earth blocks would be well worth consideration and could have significant environmental, economic, and social impacts if eventually applied to use as a building material.

Chapter 1. Introduction

Agricultural waste and plastic waste are prevalent throughout the world but especially for some countries such as Ghana which import wastes from other nations. Each year Ghana imports “over 10,000 metric tons of finished plastic products” and currently does not recollect or recycle even half of the waste that is generated (Kortei & Quansah, 2016). Additionally, agricultural waste such as coconut “husks and shells are usually thrown away or openly burned” which increase air pollution or littered landscapes which can negatively impact sanitation or drainage systems (Obeng et. al., 2020). Researching ways to add value to waste through incorporation into existing systems can promote innovative and useful inventions, benefit local economies, and offer massive environmental and sustainability benefits.

This project aimed to design earth-based building blocks that incorporate agricultural and plastic waste to further research of value-added earth construction in Ghana. First it would be necessary to research current earth-building practices in Ghana, especially those which incorporate waste. Formal peer-reviewed literature, open-source anecdotal Internet posts, and conversations with entrepreneurs in relevant fields all provided a necessary breadth of understanding of the project since building with earth is less common in the United States currently. This knowledge would inform the creation of an earth-block manufacturing process that is affordable and replicable outside of a formal laboratory setting. This process would then be utilized to build and test unstabilized compressed earth blocks which incorporate wastes that are common to Ghana, namely PET plastic bottles and coconut fibers. Determining the effects of such wastes on the strength or durability of earth blocks could encourage or inform further research or innovation for the value-addition of wastes into construction.

Unfortunately, due to the coronavirus pandemic, this project was not able to be performed in Ghana and was instead grounded in the United States. Therefore, the intention to perform this project using co-design and cross-cultural collaboration was greatly limited. Luckily, it was possible to virtually meet with or contact the following three Ghanaian individuals who aided the project through conversation or publications: Nelson Boateng, Dr. Fred McBagonluri, and Dr. Humphrey Danso. While the project was not completed using co-design, even limited interactions with Ghanaians shaped the project to hopefully become more relevant and replicable for a potential eventual application in Ghana.

Chapter 2. Background on Recycled Material Earth Construction

2.1 Earth-based Construction

While studying earth-based construction may feel somewhat obsolete for urban American engineers, about “half the world population lives in earth constructions” especially in less industrialized nations (Gomes et al, 2011; Pacheco-Togal & Jalali, 2012). Studying and potentially improving earth construction and traditional architecture has the potential to positively affect millions of lives, and achieve greater sustainability.

Concerns about strength and durability are the primary mentions regarding earth constructions in regions that can afford to import other building materials or styles (Odeyale & Adekunle, 2008; Ngowi, 1997). In general, building with earth does require a significant amount of labor to create and maintain the structure, and due to numerous variables such as weather, soil characteristics, and construction methods, the structure may fail regardless. For example, earth structures are particularly susceptible to earthquake damage. It has already been observed that earth walls are strong, however more research into the durability of earth structures is required, especially with regard to various climatic regions or specific weather patterns (Agorsah et al., 1985; Chandel et al., 2016; Celadyn, 2014).

Although construction is becoming more globalized via importing materials and architecture styles, earth construction has received more attention from researchers and developers within the past decade (Pacheco-Torgal & Jalali, 2012; Laborel-Preneron et al., 2016). Much of the research considers rammed earth or compressed earth blocks, introducing aggregates or fibers to improve mechanical properties, or blending traditional and modern materials to improve seismic performance. However, there still remain significant obstacles to being able to generalize the results and truly improve the information on earth structures. For example, in a review of 50 references by Laborel-Preneron et al. (2016), “only 4 present both the chemical composition and mechanical characteristics” of the earth constructions studied. Since soil characteristics can vary greatly by region, it is difficult to compare data from various sources especially if the study does not include that information at all. A 1997 study on Botswana earth construction further illustrates this point: the study concluded that “soil with high sand content and low clay content is more suitable for cement stabilization, while the soil with high clay content is better for lime stabilization in terms of strength” (Ngowi, 1997). Local earth construction is inherently dependent on the climate and local materials, including the characteristics of the soil. Creating frameworks for soil types may be beneficial, but it is necessary to first include that information in research and to vary soil characteristics in scientific experiments.

The cost of adopting a global construction style is high - financially, environmentally, and culturally. Many construction materials are difficult to transport, and thus it is often more expensive to use imported materials instead of local ones. The embodied energy of construction materials must also be taken into account when evaluating the sustainability of a project; if a material requires a lot of energy to extract, produces a lot of pollutants to process or manufacture, or requires considerable energy for transportation to the construction site. For example, despite being less easily renewable, slow-growing local trees may be more sustainable for a timber frame than fast-growing trees overseas, or stone from a nearby quarry may have less embodied energy for a foundation than cement blocks manufactured and shipped from miles away. Additionally, by relying on foreign nations to source materials and influence architecture, the local workforce is less utilized and the importance of regional knowledge is forfeited.

If structures with imported concrete and foreign styles require wealth and represent modernity, the use of traditional materials or styles have the danger of being used in turn to “symbolize abject poverty” (Odeyale & Adekunle, 2008). The negative perception of traditional architecture can be destructive to sustainability efforts, national identity formation, and improvements to existing knowledge systems. However, the social perspective on earth constructions as being symbolic of poverty or antiquation is a difficult obstacle to overcome (Gramlich, 2013). Due to this perception, “less developed countries try to emulate the use of unsustainable construction materials” that now many developed nations are attempting to reduce (Pacheco-Torgal & Jalali, 2012). However, traditional architecture is likely much closer to the goals of sustainable construction than conventional modern architecture is; for example, the use of passive thermal control systems is much more sustainable than high-technology or energy-hungry mechanical systems, and the use of local renewable or recyclable materials such as earth has a better environmental impact than high-polluting and fragile materials such as concrete or fired clay bricks. The arguments against using earth as a construction material are legitimate, but do not necessitate abandoning the practice. Where earth structures lack in compressive strength or durability, they make up for by offering cultural and heritage significance, improved air quality and thermal control, reduced economic impact, and environmental benefits (Ngowi, 1997; Chandel et al., 2016; Wahid, 2012; Sunakorn & Yimprayoon, 2011). More research into improving elements of traditional architecture would be beneficial, especially those which may increase the social perception or value of those elements. Since construction trends are affected by society and perceptions of status, further research into the public perception of sustainable construction and traditional architecture could help inform the potential success of adaptations to modern architecture (Ngoma & Sassu, 2004).

The research on traditional architecture is growing, but there remain gaps in the data on hand. This research has the potential to be revolutionary; already many studies have been completed that reveal how alternative construction styles or building materials can improve technical performance, increase thermal comfort, and reduce environmental impact as compared to more conventional architecture. For example, biofacades such as a wall of vines has been found to reduce daytime indoor air temperature by up to almost 5 degrees Celsius versus a conventional wall (Sunakorn & Yimprayoon, 2011), and traditional architecture carries less embodied energy, less operational energy, less carbon dioxide release, and even less construction costs when compared to conventional architecture (Chandel et al., 2016; Wahid, 2012). However, many people are simply not aware of these potential benefits or desire modern styles (Chandel et al., 2016; Celadyn, 2014), the data is not sufficient across the board (Sunakorn & Yimprayoon, 2011; Gonzalez et al., 2000), and there are not enough incentives or codal provisions to include these sustainable qualities in modern structures (Odeyale & Adekunle, 2008; Chandel et al., 2016; Celadyn, 2014).

2.2 Coconut and Plastic Waste in Ghana

Since coconut production and plastic use in Ghana are rising annually, there is a need to determine innovative waste management practices for such waste types in order to reduce the environmental impact of these products. Coconut production in Ghana is a massive industry and continually growing. In 2017, Ghanaian around 229 million coconuts were produced annually, which were "usually grown in smallholder plantations in six out of the ten regions of the country" (GEPA, 2017). While the coconut plant is lauded for its many uses, unfortunately the utilization of the inedible parts of the coconut such as the husk or shell or its fibers is limited. Instead, these parts of the coconut are disposed of in landfills, littered along the countryside, or burned (Ameko et. al., 2014). Burning or littering of coconut wastes "result in poor sanitation, air pollution and blocked roadside drains that facilitate the breeding of mosquitoes" (Obeng et. al., 2020).

In Ghana, plastic use is also a growing trend due to the increase of synthetic packaging and imported products. Every year, Ghana generates up to 12.775 kilograms of plastic per person (Koreti & Quansah, 2016). Of the 140 plastic companies in Ghana, "only 20 of them collect the byproducts and re-use it later", and only 42,000 of 210,000 tons of plastic materials imported into Ghana are either reused or recycled while the rest are simply wasted (Teye, 2012). Much like coconut waste, plastic waste is either dumped into landfills, littered, or incinerated; thus, plastic waste carries negative environmental impacts in the current waste management system. However, plastic waste is more likely than coconut waste to be collected formally or informally before it is sent to a landfill, or scavenged once it is in the landfill; this collection may have negative health impacts on the collectors, but also offers "very positive economic and social implications", which would be increased if plastic waste was better utilized as a resource (Owusu-Sekyere et. al., 2013).

2.3 Incorporating Waste in Earth Blocks

Certain natural materials have been found to perform equivalently or even better than common commercial materials for certain building purposes (Ganiron, Ucol-Ganiron, & Ganiron III, 2017; Kanna & Dhanalakshmi, 2018). Coconut is a stellar example of a natural resource that offers phenomenal benefits when applied to various industries such as construction. Coconut fibers have been shown experimentally to increase the strength properties of common construction materials such as bricks or cement hollow blocks (Ganiron Jr., Ucol-Ganiron, & Ganiron III, 2017). Even though bricks and cement blocks and that include coconut fibers have been found to improve physical and mechanical properties, coconut shells are generally considered an agricultural waste product and are not often used for other purposes. Reasons for this include, but are not limited to, cost, lack of market interest, lack of government incentive, lack of standards to overcome variations in natural materials, status quo, and lack of knowledge that alternative materials are viable options (Chan et al., 2018). However, there are some innovative individuals or organizations who have begun to advocate for the extended use of coconut, due to its remarkable qualities and prolific existence in countries such as Ghana, such as FibreWealth Limited or various artists (FibreWealth Limited, 2020). Using coconut waste products as a renewable building material could reduce environmental damage, cut construction costs by limiting imported materials, and transform the way that Ghana – and the world – evaluates sustainable construction.

Plastics have also been shown to be useful in earth blocks for various uses. For PET plastic bottles which are completely intact, they are often filled with sand and combined into a block or wall using clay or cement mortar. These bottle brick "cylinders exhibited double the compressive strength of conventional concrete cylinders" and were also cheaper to manufacture (Muyen et. al., 2016). There also exists research of PET plastic increasing compressive strength when it is shredded and incorporated into a compressed earth block (CEB). A 2019 study concluded that the addition of 1% shredded plastic increased the compressive strength and erosion rate of a CEB by 244.4% and 50%, respectively, when compared to a CEB without any waste addition (Akinwumi et. al., 2019). Similarly, a study which considered the effects of the matrix of incorporation for various natural or plastic shredded fibers on a stabilized clay block found that the addition of shredded plastic increased the compressive strength of a block more than three times that of a traditional mud brick (Binici et. al., 2005).

In Ghana, research on incorporating natural fibers or plastic wastes in building materials have already been experimented. For CEBs with between 0.25 to 0.5 percent of coconut coir by weight, the compressive strength increased by 41% compared to an unreinforced CEB (Danso et. al., 2015). This suggests that this project will have greater relevance in Ghana where experiments to reinforce earth blocks with natural fibers are already being conducted, than in the United States where earth is less popular as a building material. Ghanaian company Toa House builds houses using sand-filled plastic bottle brick walls that are "33 percent less costly" than houses that use cement blocks, yet are "also earthquake resistant, energy efficient, well insulated, and 20 times stronger" (Anim, 2017). Similarly, the Ghanaian company Nelplast shreds and melts most types of plastics to create pavement blocks that are "70 percent plastic and 30 percent sand without any cement" and are "800 percent stronger than ordinary pavement blocks" (MESTI, 2018). Additionally, a Ghanaian study on the effects of melted polyethylene (PE) plastic and roughly 43% by weight of coconut coir showed that the composite material increased compressive and flexural strength by 125% and 31.46%, respectively, when compared to the control with no coconut fiber (Amoako et. al., 2018). The research and entrepreneurship that already exists in Ghana of utilizing either natural coconut or plastic wastes in building materials shows that there is a market for or interest in value-added resources, and that experiential knowledge and expertise already exists locally.

2.4 Cross-Cultural Design

For cross-cultural projects, achieving a level of mutual respect and understanding is essential to creating a successful result. In a traditional engineering design process, the engineers are considered the experts and design is often a linear, top-down process. However, by acknowledging that the communities which would actually use the product have invaluable experiential knowledge about the subject helps create a space where design is a more open process. Co-designing a solution to simultaneously alleviate waste stream problems and innovate traditional earth construction with Ghanaians may help increase the success of this research or the relevance of this work for Ghanaian communities. For example, a solution that is technically sound but locally irrelevant would ultimately be unsuccessful.

Due to the global pandemic, the opportunities for co-design and mutual learning in this project were restricted. However, there still exist tangible ways to achieve a successful cross-cultural collaboration that can lead to a result which will truly benefit both parties involved. By creating processes and sharing preliminary results with universities in the United States and Ghana, namely Academic City College, the process of design and building a solution will help alleviate cultural or technological differences between parties. Despite having some access to a technical university laboratory to complete this project, the solution must be able to be replicated in Ghana, likely outside of a laboratory. Collaborating with like-minded companies in Ghana, like Nelplast, will allow for bridging an understanding of the social perspective and technical capabilities of this work for Ghana.

In order for the project to be successful, it is necessary to respect the varying backgrounds and expertise of all parties involved. By working with Ghanaian community members instead of simply with them in mind, it becomes more likely to create a solution that will be useful in Ghanaian communities. Ultimately, the goal of this project is to have a positive impact on Ghanaian communities while also contributing to technical research that can be applied to other communities. Despite being unable to be physically present in Ghana, collaborating directly with communities, and completing this research with Ghanain resources on hand, it is still possible and essential to co-create the solution with Ghanaians.

Chapter 3. Creating and Testing Value-Added CEBs

Before beginning the experimentation elements of this project, a review of published literature was completed to provide a foundational understanding of the numerous components within this project. While originally the project was intended to be carried out in Kyebi, Ghana, it was grounded in Worcester, MA, USA, due to the coronavirus. Due to the combination of equipment or resource availability in Ghana as well as coronavirus-related restrictions on WPI laboratory operations, the project necessitated being reimagined in order to be at least partially completed outside of a formal laboratory setting. This new remote nature significantly impacted the project objectives, timeline, methodology, and co-design capabilities. However, the resulting laboratory-independent methodology may be more accessible or replicable in Ghana.

3.1 Timeline:

Our project was completed over two months in the winter of 2021. Figure 1 below outlines the timeline of preparing, creating, and analyzing the experiments with earth-based building bricks.

WEEK	OBJECTIVE
1	- Reimagine project for remote capabilities
2	- Verify specific project goal and plans
3	- Design block mold 1 - Gather required materials
4	- Prototype mold design 1 - Produce first batch of blocks
5	- Prototype mold design 2
6	- Produce final batch of blocks
7	- Experimentation of block properties
8	- Data analysis and create final deliverables

Figure 1. Project Timeline

3.2 Production of UCEBs

Our compressed earth blocks were primarily a mixture of soil and water. This study explored the effects of the addition of coconut coir fiber and PET plastic fiber mixed throughout, at varying compositions. Due to the lack of a chemical binding agent such as cement or lime, these blocks were considered unstabilized compressed earth blocks (UCEBs). The fibers were thus considered more of an aggregate than a binder. The coconut coir fibers were too thin to accurately measure a diameter, and the PET plastic fibers were roughly 2 cm wide and 4 cm long strips. The soil used was commercial potting soil, and was assumed to not be clayey or silty.

The soil was sieved with a ¼ inch mesh, and weighed using a kitchen scale which was accurate to ±1 gram. The soil was not dried before weighing, but simply taken straight from the potting soil bag. Water was then added to the soil at roughly 15% weight of dry soil. The soil and water were thoroughly mixed before the addition of the aggregate(s). The fibers were weighed then mixed into the soil in stages to achieve a more uniform fiber distribution before being (Subramaniaprasad et al, 2014).

The block samples were prepared by filling a wax-paper-lined wooden mold with a 4-inch-sided square cuboid cavity. The amount of soil mixture required to fill the cavity was decided by density calculations, and trial and error. Once the mold was filled, the lid was placed on top, and compressed into the mold using a hand-cranked arbor press. The use of a hand-cranked press may result in less overall pressure but a slower compaction rate than a hydraulic press; a slower compaction rate may slightly increase the density and compressive strength as well as lower the erodibility of the blocks (Danso, 2016) After compression, the mold was taken apart around the formed block, and the wax paper helped prevent block deformations during removal and transportation to a drying location. The blocks were air-dried indoors for 5 days until testing. Ideally, the blocks would dry for weeks (Bogas et. al., 2019; Danso et. al., 2015; Binici et. al., 2003) or in an oven for at least 2 days (Danso, 2016), but the drying time was shortened due to time constraints, the small size of the blocks, and the lack of chemical stabilizer used. It is important to note that measured properties of UCEBs depend on when the material is tested, and thus the resulting data may be limited by this expedited drying timeline.

3.2.1 Explanation for Testing UCEBs

The decision to test UCEBs considered time, material availability, ease of (re)production, sustainability, and relevance as the most important factors. Stabilizers such as cement or lime were avoided due to the availability and cost of such materials in Ghana, curing time requirements of between 7 to 28 days, and negative environmental impacts of processing such materials. By testing UCEBs reinforced with various compositions of waste fibers, this methodology and the data produced will likely be more replicable and sustainable for Ghana than other variables or current practices.

Initially, this project aimed to study compositions of fired bricks. Fired bricks are common in architecture due to good mechanical properties and long-standing manufacturing traditions. They are made by mixing primarily clay and water (and can also include natural fiber aggregates), drying for 7 days, and then firing in a kiln. While mixing and molding the bricks may have been easier than UCEBs, the requirement to both dry and fire bricks was deemed inappropriate with the timeline and limited kiln availability. Additionally, it was difficult to determine the availability of clayey soil in Ghana, the environmental and health impacts of firing the bricks, and the ability to include plastic aggregates in the study. Unfired bricks were not strongly considered for this project because of their generally poor mechanical and durability properties.

3.3 Experimental Design

3.3.1 Variable Waste Composition of UCEBs

The independent variable in this study was the composition of waste fibers in the soil mixture of the UCEB. From literature, the optimal addition of fibers as an aggregate in compressed earth blocks is between 0.25 and 0.5 percent by dry weight of coconut fiber (Danso et. al., 2015) and between 0.1 and 0.2 percent by dry weight of plastic fiber (Binici et al., 2005). Table 1 below outlines the various compositions of waste fibers that were produced during this study, which were decided in part by the limited timeline of the project as well as the minimum reading requirement of the kitchen scale which was used in the UCEB production process.

Table 1. Composition of Waste Fibers in Blocks by Weight Percent of Dry Soil

Composition	Coconut Weight %	Plastic Weight %
Control	0	0
Plastic	0	0.2
Coconut	0.4	0
Mixture	0.4	0.2

While the method of incorporation of fibers could also have been varied for additional results, it was decided that studying weight percent would have more meaningful results for such scaled-down blocks. When fibers and soil are added to the CEB mold in distinct layers, the matrix of the fibers does have some effect on the properties of the CEB (Binici et al., 2005). However, it was decided that including two independent variables would complicate the project in a way that the restricted timeline would not allow. The decision to study composition over matrix was informed by the ability for well-dispersed fiber aggregates to improve tensile strength (Danso et. al., 2015; Donkor & Obonyo, 2015).

3.3.2 Testing UCEB Properties

Our study considered the physical properties of density and shrinkage, the mechanical property of flexural strength, and the durability property of erosion rate. All tests occurred when the UCEBs had dried over a duration of 5 days. The percent change of the shrinkage and density was found by measuring the block with a ruler, weighing the block with a scale, and calculating percent change from wet to dry with Equation 1 below. The flexural strength test was a three-point-bending test designed to be performed outside of a laboratory, with the blocks sitting on two wooden stands and the center 3 inches unsupported. Known weights were incrementally placed on the center of the block until failure (see Figure 2), and then the flexure stress at failure was calculated with Equation 2 below. The erodibility test was performed by constantly dripping water on the blocks for 25 minutes (to simulate driving rain) and measuring the depth of the pit created in the block. The erosion rate was calculated using Equation 3 below.

Table 2. Equations Used to Calculate Various UCEB Properties

$\Delta\rho\ (\%) = \frac{\rho_{Wet} - \rho_{Dry}}{\rho_{Wet}} * 100\%$	$\sigma_F = \frac{3FL}{2WH^2} = \frac{3 * F * 3\ in}{2 * 3.5\ in * 1\ in^2} = \frac{1.286 * F}{in^2}$	$E = \frac{D\ (mm)}{T\ (min)}$
Equation 1. Percent Change	*Equation 2. Yield Flexural Stress*	*Equation 3. Erosion Rate*

Figure 2. Control UCEB at Failure during Flexural Strength Test (Desmarais, 2021)

Chapter 4. Mold Designs and Analysis of Blocks

4.1 CEB Mold Iterative Design Process

Due to earth building being less popular in the United States than in Ghana, creating a process to manufacture small UCEBs required an iterative design approach. Thus, the process was hypothesized and altered based on the results obtained at each step. Additionally, due to certain timeline, equipment, and project intention determinations, it was necessary to constrain the mold design to be simple, affordable, relatively short, and easily replicable using minimal laboratory materials. Initially, the mold was designed very simply to be 2x4 planks of wood screwed together to achieve a 4-inch cuboid empty center. The mold would act as a collar to the soil, and was designed to be used in conjunction with a wooden base wider than the mold and thick enough to support the force of the press (i.e., 2x10x10 inches), and a top that perfectly fit into the cross-section of the mold hole and was thick enough to manage and distribute the force from the press onto the block (i.e., 2x4x4 inches). To remove the block from the mold, the collar would be placed on 2x4 stands, and the block would be pressed out onto the base piece by the arbor press and top piece.

Due to the naming convention of wood, a nominal 2x4 inch plank in fact has actual dimensions of 1.5x3.5 inches, and as such the mold created a 5x3.5x1.5 inch rectangular empty center (see Appendix A). The intended volume within the mold collar was reduced by roughly 4.3%, but likely benefited the project because the mold required slightly less material to fill than the intended design would. Additionally, since building blocks tend to be of different width than length, this unintended design change created blocks that were potentially more directly scalable to current practices.

With the first prototype of the mold design, the planks were screwed together so that the mold was slightly wobbly in a way barely perceptible to the naked eye. However, this imperfection became clear when the first blocks were being pressed because more water and even a small amount of soil was pushed out from below the mold on the slightly raised side than on the level side. Initially, the soil mixture was filled directly into the mold and compressed. It was found that using a mallet to tap the block from the mold caused too many vibrations through the block and essentially reversed the compression process, destroying the block. When the mold was placed on the stilts to press the block out of the collar, the friction on the sides of the mold was strong enough to require forcing the block from the mold and resulted in deformations. Additionally, moving the block from the base without further deformations was challenging because the block was still wet, somewhat fragile, and had no handles. In order to reduce friction on the blocks, the mold was lined with wax paper before being filled with the soil mixture. The addition of the wax paper worked two-fold; it eased the process of pressing out the blocks from the collar, reduced but did not eliminate deformations from removal, and it also acted as a handle for transporting the blocks more safely from the base to the drying area.

The second prototype of the mold followed the same design as the first, but was fabricated more carefully so that it was more level. This greatly reduced the material that was pushed out from the mold during compression. Overall, this mold functioned well, but the deformations from needing to force out the blocks after compression using the arbor press should be avoided. Thus, not only would the mold require redesign, but the approach to block removal would need to be improved as well.

The second design of the mold replaced the regular screws with wing screws so that the collar was no longer fixed together (see Appendix B). This way, instead of pressing the block out of the mold after compression, the mold would be unscrewed and taken apart around the block itself. Although this slightly increased the cost of the mold due to the wing screws, the mold was still much less expensive than a commercial mold or CINVA ram. Wax paper was still used as a liner on the mold to reduce the chances of the block sticking to the walls as the mold was being taken apart. Ultimately, the new mold worked much better because less deformations were visible on the blocks. The blocks made with this new mold were thus considered the final blocks and were set to dry for five days before they were able to be tested for property analysis.

4.2 Properties of CEBs

Each block tested was pressed with the second mold design, measured and weighed right after compression, dried in ambient indoor air for five days, and then subjected to subsequent property tests as described previously. Although the sample size of the final testable blocks was very small, the results obtained were very promising (see Table 3).

The shrinkage test produced nominal results. The density of the blocks reduced on average 22.4%, with a standard deviation of 1.6, when calculated from wet to dry blocks. These results suggest that the incorporation of plastic and/or coconut waste does not significantly affect the physical properties of density and shrinkage as compared to the control blocks.

The champion results from these tests are those from the flexural strength test. When placed on the stands, the control block was unable to support its own weight, let alone any additional load, and collapsed immediately. In comparison, the blocks with coconut, plastic, and a mixture of coconut and plastic were able to hold on the stands and could support a load of 600, 1025, 1215 grams respectively. Thus, the incorporation of PET plastic waste fibers exponentially increased the flexural strength of the blocks, and the mixture of both coconut and plastic fibers achieved the highest flexural stress at failure. This signifies that the maximum flexural stress of UCEBs was significantly improved with the incorporation of waste fibers and should be further studied. According to Danso et. al. (2015), this result may also point to an increase in the maximum compressive strength of the blocks, but this is outside of the scope of this particular study.

The erosion rate of the blocks did increase with the addition of waste fibers. With one waste type, the erodibility was doubled, and was tripled with both waste types incorporated. While erodibility is a drawback of waste-incorporated UCEBs, there is potential that the blocks could be preserved by using plaster and even perhaps mortar between the blocks. In fact, the practice of plastering the face of an earthen wall is traditionally and currently very common precisely for its low durability trends (Santos et. al., 2019). Ultimately, an increased erosion rate is not ideal but also very capable of being circumvented through the use of finishing materials such as plaster; studying the effects of this finishing material would yield interesting results and may improve the viability of using waste fibers in UCEBs.

Table 3. Property Analysis of UCEBs

	Physical	Mechanical		Durability
Composition	**Average Density Change (%)**	**Max Flexural Load (N)**	**Flexural Stress at Failure (N/m^2)**	**Erosion Rate (mm/min)**
No Waste	23.633	0	0	0.245
Plastic	20.066	10.05	20,036	0.508
Coconut	22.474	5.8	11,729	0.508
Mixture	23.260	11.9	23,750	0.762

4.3 Social, Environmental, and Economic Impacts

The motivation of this project was to study potential low-cost and sustainable building materials. By limiting the materials utilized to only those which would be available and widely accessible in Ghana, such as wood, soil, and waste products, this project reduces the dependence on high-cost, unsustainable, or imported materials that are often used in construction such as metal or cement. The use of local materials helps reduce costs but also greatly increases the sustainability elements of a project because less emissions are required to manufacture or transport materials. One cost that remains to be considered is the cost of collecting the waste materials required for this purpose. However, increasing the value of such waste products has the potential to also add value to the livelihoods of waste management workers, and thus benefit the local economy in a multitude of ways.

While this project represents the first of many studies before determining what waste compositions may be viable for earth construction, this project's independence on a formal laboratory carries with it the social impact of providing options to people with limited resources to perform their own research and build their own solutions. Thus, innovations for sustainable construction materials or low-cost housing need not be limited to academics or private corporations.

Additionally, simply the practice of increasing academic attention on earth-building practices and cross-cultural sustainability innovations may contribute positively to the valuation of various types of knowledge and experience. Research which aims to respect and build upon existing and viable traditions instead of aiming to change or eliminate traditional practices can set a precedent of achieving cross-cultural respect and understanding instead of promoting homogeneity or universalization. Earth buildings have been shown to offer various health benefits compared to those which use manufactured materials (Danso, 2013). By supporting the use of earth as a building material and studying ways to make it stronger and more competitive against manufactured materials which are popular in highly industrialized regions, construction may become far more sustainable across many regions.

4.4 Limitations to Testing CEBs

This project aimed to determine the effect of utilizing both natural and synthetic types of waste fibers, respectively coconut husk and PET plastic, and was informed by previously published studies which only considered one of each waste type. Additionally, much of the existing research on earth blocks focuses on stabilized CEBs, whereas this project aimed to determine the effects of waste on unstabilized CEBs. The operating assumptions for this project were first that multi-type waste fibers would increase the strength of blocks since single-type waste fibers have been shown to perform better, and secondly that excluding the use of chemical stabilizers such as cement or lime would increase the sustainability of the project, reduce the timeline, yet likely limit the properties of the blocks created. This section will discuss the various external limitations and methodological weaknesses of this project.

The most pressing external limitations to this project were the restrictions due to the short timeline and the coronavirus pandemic. This project was intended to be completed over a course of eight weeks in Ghana. From literature, earth blocks tend to require at least one to four weeks of drying time before they are able to be tested or used, so the project was immediately limited in determining how many batches of blocks could be tested within the given timeframe.

The pandemic removed the ability to travel to Ghana and work directly with Ghanaian communities, and thus severely affected the opportunity to include experiential knowledge of building with earth in the project background or design of the experiments. Therefore, designing an earth block manufacturing process took longer than had been expected since it was less possible to start from a current practice. As such, the already limited number of batches that could be produced, dried, and tested using the same process was limited even more. Due to being grounded in wintry Massachusetts and laboratory restrictions, the blocks were unable to dry outside under the hot Ghanaian sun and instead needed to be transported away from the laboratory to dry inside. For an entire batch of blocks, this transportation presented deformations on the blocks which rendered them unable to be tested for this project. Each composition tested only consisted of two final blocks, with only one of each composition tested for either the mechanical or durability property. There could not be more tests performed due to the very low number of final blocks produced, and the tests which were performed failed at being statistically relevant. Therefore, the results are promising, but cannot be considered reliable or replicable due to the low number of blocks. Additionally, due to the coronavirus restrictions, the project was required to be remote for the first three weeks and thus laboratory equipment or material usage was suspended until later than originally expected within the already limited timeline.

The main methodological weaknesses of this project were the decisions to not include stabilizer and to create a laboratory-independent process. Avoiding chemical stabilizer such as cement or lime, which are often used in earth buildings or CEBs did reduce the cost, environmental impact, and curing/drying time of the blocks before testing - but it also affected the property analysis of the blocks. If cement had been incorporated into the blocks, it is likely that the shrinkage would have been more significant, the flexural strength would have increased, and the erodibility would have been reduced.

Limiting the dependence on and utilization of laboratory equipment in order to make a more replicable process did affect the creation of a manufacturing process and the data collected on the blocks that were produced. This restricted the ability to characterize the soil used in the project, and thus the results will be less relevant for replication if different soil types are used. Due to specific attention to safety measures using the WPI laboratory, this project was unable to include heating the plastic which is a key element in the Nelplast manufacturing process. Thus, the conversations with and insight from Nelson Boateng became less directly relevant to this specific study and its process became more variable to iterative design. Additionally, by restricting the use of formal laboratory technology or equipment, the arbor press and kitchen scale used were relatively rudimentary. The height of the arbor press opening restricted the size of the mold and made it so the blocks produced were very scaled-down versions of a standard building block. The kitchen scale used to weigh the materials was accurate only to the gram, and so the measurements were not incredibly precise; however, this may be more representative of what an earth block process would be in Ghana especially at a large scale where very specific measurements may be too expensive or time-consuming to achieve.

Chapter 5: Recommendations and Conclusion

5.1 Recommendation for Further Research

The purpose of this project was not to provide a methodological solution for the waste or housing problems in Ghana, but to exhibit potential improvements to consider and to encourage future research or innovation. Future research may include variations which consider the following possibilities:

- Utilizing a CINVA ram instead of a wooden mold (which would increase the uniformity of the blocks but would also increase the cost impact of the work)
- In-depth soil characterization and varied soil types used for the blocks (which would increase the dependence on a formal laboratory setting but would increase the ability to create standards for earth building)
- Increasing the variety of waste fiber types or compositions
- Vary the methods of waste fiber incorporation into the block
- Vary the methods of drying the blocks
- Utilizing stabilizers (which would increase the environmental and economic impact of the blocks but may also increase block performance)
- Vary the size and shape of the blocks

This list of possibilities to study are in no means comprehensive and showcases how new and groundbreaking the field of value-added building materials really is. Building with earth is difficult to standardize and develop building codes for, yet there are immense benefits of researching ways to develop knowledge of this practice. Incorporating wastes to strengthen earth building materials is an exciting subset of sustainable construction, which still requires much attention from academics or innovators. Because this project was completed externally from Ghana, this project lacks the location-specific experiential knowledge that would likely inspire more relevant and innovative methodologies and recommendations. Thus, there stands a recommendation for any cross-cultural research pursuit to consider a co-design approach in order to include experiential knowledge as well as academic expertise.

This project hinged upon the experience and existing work of three Ghanaian individuals who were already working on similar projects or interested in the results of further research into waste-incorporated earth blocks. Due to the lack of direct co-design opportunities and the unique limitations presented by the coronavirus pandemic, the results of this project are not as transferable to communities but can nonetheless provide inspiration for researchers or entrepreneurs who aim to add value to waste for its incorporation into building materials. Perhaps the most promising considerations would be within Ghana itself, whether through educational institutions, commercial or entrepreneurial companies, or innovate and motivated individuals. However, continuing research externally such as in subsequent WPI projects will also improve the breadth of information available. It may be helpful for Ghana to increase documentation of soil characterization in specific regions of the country or to further document local practices of building with earth, especially informally in order to improve the relevance of external research.

5.2 Conclusion

This project aimed to design earth-based building blocks that incorporate agricultural and plastic waste to further research of value-added earth construction in Ghana. In order to fulfill this objective, it was necessary to complete background research, create an earth block manufacturing process, and analyze the effects of waste incorporation on the blocks' properties. Due to the intention to improve sustainable material use and maintain very low costs, it was necessary to work under the assumption that all materials used must be locally available and affordable in Ghanaian communities. Thus, the project avoided any use of cement or lime as stabilizer, both to reduce cost and to avoid the potential negative environmental effects of those materials. Additionally, the block mold was designed to be very simple, low-cost, and easy to fabricate and use outside of a formal laboratory setting.

Despite challenges due to the cross-cultural and short-term aspects of the project, the results obtained from especially the mechanical properties of the waste-incorporated blocks are optimistic that the intentions of this study deserve further research and attention. Because this project was intended for an external community, the best chance for the project to have relevant and desirable results was to work with the community directly. Unfortunately, due to travel restrictions from the coronavirus pandemic, this co-design opportunity was also restricted, and as such the project was unable to be as informed and co-designed with Ghanaian experts. Therefore, the block mold, manufacturing process, and all results obtained within the project were more strained for time, received less experienced guidance, and are less likely to be relevant to Ghanaian communities without further research using their local materials, practices, and experience. However, because the blocks with PET plastic waste and/or coconut husk waste fibers performed better than the control blocks under the flexural strength tests, the results in this study are promising nonetheless. This study concludes with a recommendation for future research of waste-incorporated earth blocks to continue and for further entrepreneurship or innovation of the value-addition of common waste items.

Citations:

Adam, I., Walker, T. R., Bezerra, J. C., & Clayton, A. (2020). Policies to reduce single-use plastic marine pollution in West Africa. *Marine Policy*, *116*, 103928.

Addo, H. O., Dun-Dery, E. J., Afoakwa, E., Elizabeth, A., Ellen, A., & Rebecca, M. (2017). Correlates of domestic waste management and related health outcomes in Sunyani, Ghana: a protocol towards enhancing policy. *BMC public health*, *17*(1), 1-10.

Agorsah, E. K., Atherton, J. H., Connah, G., Goucher, C. L., Halbar, B. G., Kense, F. J., ... & Shinnie, P. L. (1985). Archeological Implications of Traditional House Construction Among the Nchumuru of Northern Ghana [and Comments and Reply]. Current Anthropology, 26(1), 103-115.

Akinwumi, I. I., Domo-Spiff, A. H., & Salami, A. (2019). Marine plastic pollution and affordable housing challenge: Shredded waste plastic stabilized soil for producing compressed earth bricks. *Case Studies in Construction Materials*, *11*, e00241.

Ameko, E., Achio, S., Kutsanedzie, F., Abrokwah, A., Laar, D., & Goddey, J. T. A. P. (2014). Conversion of three types of waste biomass in Ghana (coconut shell, coconut husk and mahogany) into liquid smokes and determination of the sensory profiles. Int. J. Eng. Res. Technol, 3(12), 1107-1114.

Amoako, G., Mensah-Amoah, P., Sam, F., & Sackey, S. S. (2018). Some mechanical properties of coconut fiber reinforced polyethylene composite to control environmental waste in Ghana. Energy and Environment Research, 8(1), 1.

Anim, P. (2017). The Toa House Story: Building Homes using Plastic Bottles. Retrieved March 26, 2021, from https://blog.meqasa.com/toa-house-ghana-eco-housing/

Binici, H., Aksogan, O., & Shah, T. (2005). Investigation of fibre reinforced mud brick as a building material. *Construction and building materials*, *19*(4), 313-318.

Bogas, J. A., Silva, M., & Glória Gomes, M. (2019). Unstabilized and stabilized compressed earth blocks with partial incorporation of recycled aggregates. *International Journal of Architectural Heritage*, *13*(4), 569-584.

Celadyn, W. (2014). Durability of buildings and sustainable architecture. Czasopismo Techniczne.

Chan, A. P. C., Darko, A., Olanipekun, A. O., & Ameyaw, E. E. (2018). Critical Barriers to Green Building Technologies Adoption in Developing Countries: The Case of Ghana. *Journal of Cleaner Production*, *172*, 1067–1079. doi: 10.1016/j.jclepro.2017.10.235

Chandel, S. S., Sharma, V., & Marwah, B. M. (2016). Review of energy efficient features in vernacular architecture for improving indoor thermal comfort conditions. *Renewable and Sustainable Energy Reviews*, *65*, 459-477.

Danso, H. (2013). Building houses with locally available materials in Ghana: benefits and problems. *International Journal of Science and Technology*, *2*(2), 225-231.

Danso, H. (2016). Influence of compacting rate on the properties of compressed earth blocks. *Advances in Materials Science and Engineering*, *2016*.

Danso, H., Martinson, D. B., Ali, M., & Williams, J. B. (2015). Physical, mechanical and durability properties of soil building blocks reinforced with natural fibres. *Construction and Building Materials*, *101*, 797-809.

Desmarais, M. (2021, Februrary-March). [Photograph Collection].

Donkor, P., & Obonyo, E. (2015). Earthen construction materials: Assessing the feasibility of improving strength and deformability of compressed earth blocks using polypropylene fibers. *Materials & Design*, *83*, 813-819.

FibreWealth Limited. (2020) FibreWealth Limited Facebook Page. Retrieved from https://www.facebook.com/fibrewealth

Ganiron Jr, T. & Ucol-Ganiron, N. & Ganiron III, T. (2017). Recycling of Waste Coconut Shells as Substitute for Aggregates in Mix Proportioning of Concrete Hollow Blocks. *The*

Scientific World Journal. 77. 107-123. Retrieved from https://www.researchgate.net/publication/257099368_Recycling_of_Waste_Coconut_Shells_as_Substitute_for_Aggregates_in_Mix_Proportioning_of_Concrete_Hollow_Blocks

Ghana Export Promotion Authority (GEPA). (2017). Coconut from Ghana. Retrieved March 26, 2021, from https://www.gepaghana.org/import/ghana-product/coconut-from-ghana/

Gomes, M. I., Lopes, M., & De Brito, J. (2011). Seismic resistance of earth construction in Portugal. *Engineering Structures*, *33*(3), 932-941.

Gonzalez, E., Machado, M. V., Rodriguez, L., Leon, G., Soto, M. P., & Almao, N. (2000). VBP-1: a sustainable urban house for low-income family in a tropical climate. In *PASSIVE AND LOW ENERGY ARCHITECTURE CONFERENCE*.

Gramlich, A. (2013). A concise history of the use of the rammed earth building technique including information on methods of preservation, repair, and maintenance.

Kanna, G. V., & Dhanalakshmi, G. (2018). Experimental Investigations on Bricks with the Replacement of Coconut Fibre. *International Research Journal of Engineering and Technology*, *05*(02). Retrieved from https://www.irjet.net/archives/V5/i2/IRJET-V5I248.pdf

Kortei, Nii & Quansah, Lydia. (2016). Plastic waste management in Ghana. Daily Graphic.

Laborel-Preneron, A., Aubert, J. E., Magniont, C., Tribout, C., & Bertron, A. (2016). Plant aggregates and fibers in earth construction materials: A review. *Construction and Building Materials*, *111*, 719-734.

Ministry of Environment, Science, Technology & Innovation (MESTI). (2020, May 19). MESTI embraces innovative use of plastic waste. Retrieved March 26, 2021, from https://mesti.gov.gh/mesti-embraces-innovative-use-plastic-waste/

Muyen, Z., Barna, T. N., & Hoque, M. N. (2016). Strength properties of plastic bottle bricks and their suitability as construction materials in Bangladesh. Progressive Agriculture, 27(3), 362-368.

Ngoma, I., & Sassu, M. (2004, August). Sustainable African housing through traditional techniques and materials: a proposal for a light seismic roof. In Proceedings of the 13th World Conference on Earthquake Engineering, Vancouver, BC, Canada (pp. 1-6).

Ngowi, A. B. (1997). Improving the traditional earth construction: a case study of Botswana. *Construction and Building Materials*, *11*(1), 1-7.

Obeng, G. Y., Amoah, D. Y., Opoku, R., Sekyere, C. K., Adjei, E. A., & Mensah, E. (2020). Coconut Wastes as Bioresource for Sustainable Energy: Quantifying Wastes, Calorific Values and Emissions in Ghana. Energies, 13(9), 2178.

Odeyale, T. O., & Adekunle, T. O. (2008). Innovative and sustainable local material in traditional African architecture–Socio cultural dimension. Structural analysis of historical construction: Preserving safety and significance, 991-998.

Owusu-Sekyere, E., Osumanu, I. K., & Abdul-Kadri, Y. (2013). An analysis of the plastic waste collection and wealth linkages in Ghana.

Pacheco-Torgal, F., & Jalali, S. (2012). Earth construction: Lessons from the past for future eco-efficient construction. *Construction and building materials*, *29*, 512-519.

Santos, T., Faria, P., & Silva, V. (2019). Can an earth plaster be efficient when applied on different masonries?. Journal of Building Engineering, 23, 314-323.

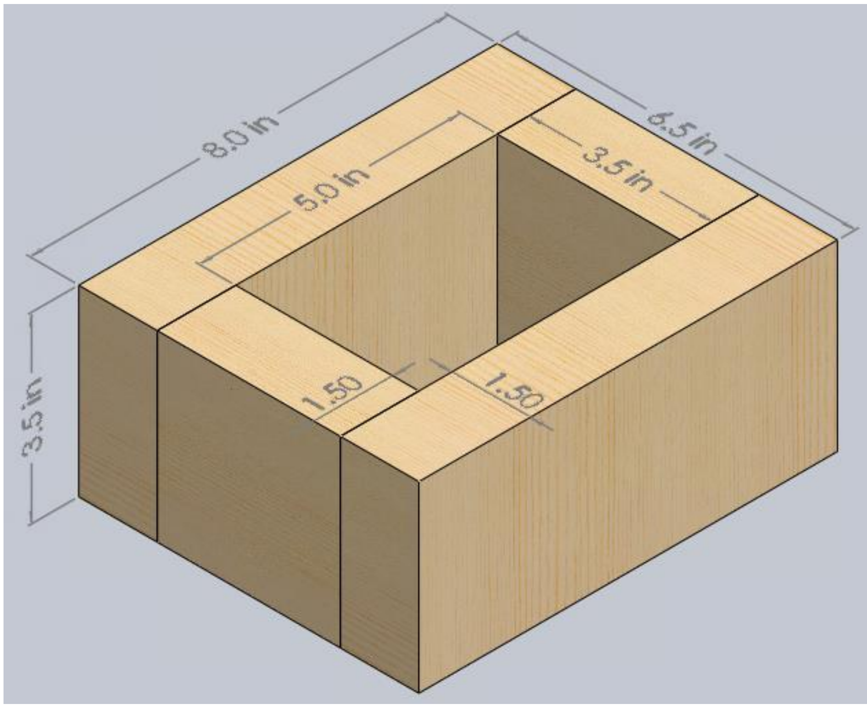
Subramaniaprasad, C. K., Abraham, B. M., & Kunhanandan Nambiar, E. K. (2015). Influence of embedded waste-plastic fibers on the improvement of the tensile strength of stabilized mud masonry blocks. *Journal of Materials in Civil Engineering*, *27*(7), 04014203.

Sunakorn, P., & Yimprayoon, C. (2011). Thermal performance of biofacade with natural ventilation in the tropical climate. *Procedia Engineering*, *21*, 34-41.

Teye, R. (2012). Plastic waste management in Accra, Ghana.

Wahid, A. (2012). Adaptive vernacular options for sustainable architecture. J Int Soc Study Vernac Settl, 2, 74-85.

Appendix A: First Mold Design Iteration and Blocks



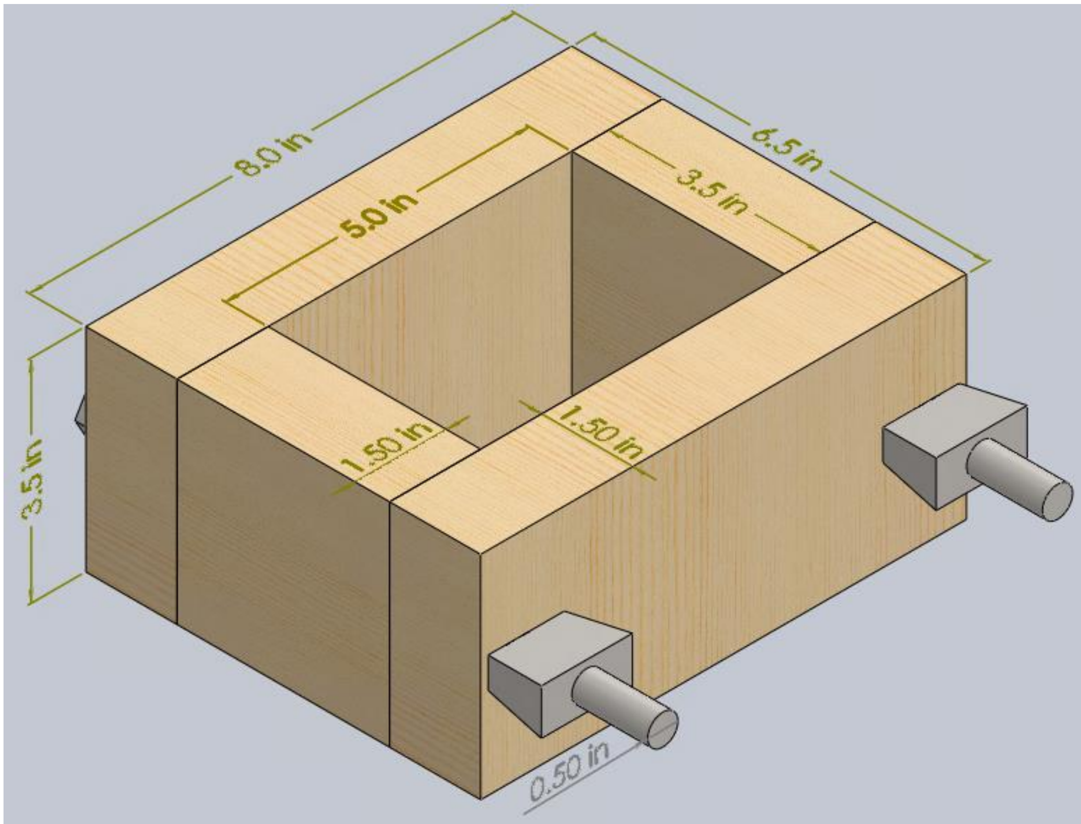
SolidWorks design of first mold, with dimensions.

Completed fabrication of first mold design lined with wax paper (Desmarais, 2021).

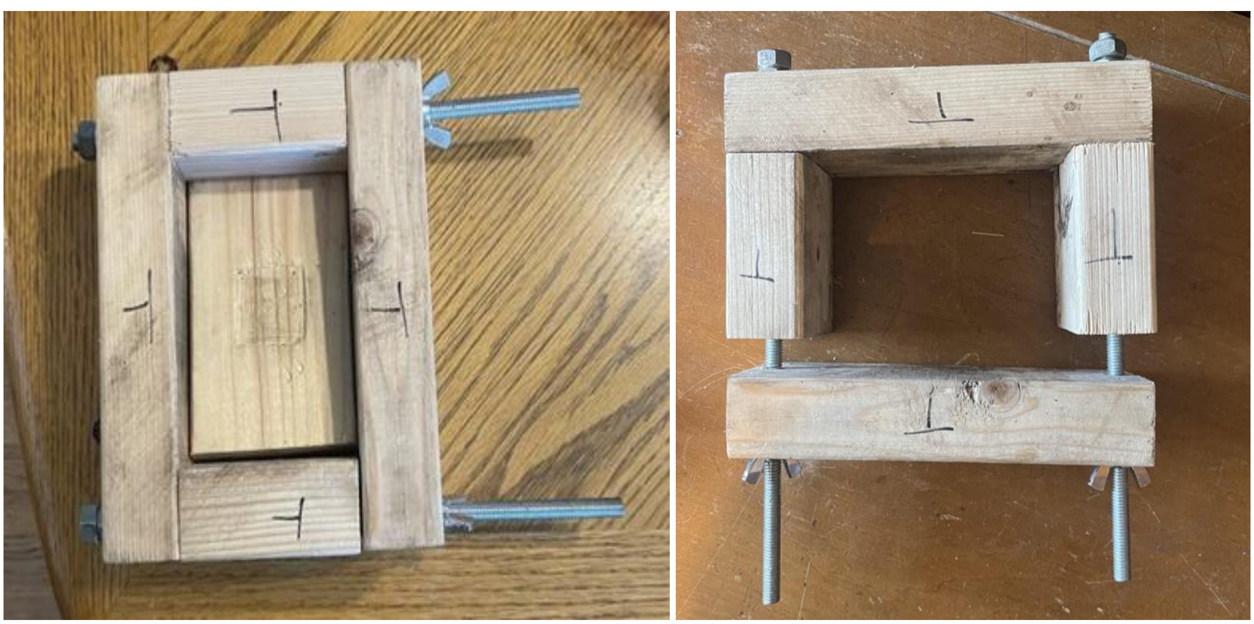
First Mold on Stilts, Finished Block Pressed Out of Mold Collar (Desmarais, 2021).

Sample block produced from first mold, with removal deformations (Desmarais, 2021).

Appendix B. Second Mold Design Iteration



SolidWorks drawing of first mold design, with dimensions.



Photos of second mold design after fabrication (Desmarais, 2021).