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

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Abstract

Our project aimed to reduce the impacts of agricultural and plastic waste by incorporating them in earth-based building blocks for construction in Ghana. In order to reach our goal, we set out to research current earth-building practices. We met with local Ghanaians who focus on this effort such as Nelson Boateng, an entrepreneur doing similar work in Ghana, to learn important information about this project effort in Ghana. We also created an earth block manufacturing process; it was necessary to ensure ease of replicability of this process in Ghana. For this reason, we only used materials that are naturally found in Ghana, such as dirt, plastic, and coconuts. This was an iterative design approach using three different iterations of a wood mold before perfecting the block manufacturing process. Lastly, we built and tested our waste incorporated blocks. There were three sets of experiments performed on our blocks to analyze their use as alternative building materials. The blocks containing waste performed significantly better in several of the mechanical categories. Specifically, the waste mixture block was able to withstand the largest maximum flexural load. The soil control block performed the best in the erosion rate test. In conclusion, more research into Unstabilized Compressed Earth Blocks with more than one waste material is needed in order for it to be a practical substitution for other building practices.

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Authorship

While many sections of this report were edited by both members of the team, this list outlines the primary authors of each section.

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Executive Summary

Plastic and coconut pollution cause problems for the environment of Ghana. Ghana has seen a steady increase in plastic consumption over the last several decades. This is largely due to a shift in packaging of food and water. The packaging is often discarded onto sidewalks, gutters, and other unregulated dump areas. This leads to pollution in the drainage system in urban areas. Plastic accounts for 9% of pollutants in waste streams according to composition studies (Fobil & Hogarh, 2006). One use of plastic packaging that has skyrocketed in Ghana is plastic water bottles. Coconuts, a popular item in Ghana, are also accumulating in streets causing further waste issues. There are many uses for several parts of the coconuts but the outer shells, or husks, are often piled up in gutters. The husks can clog drains leading to rising mosquito populations. The shells take a long time to decompose and occasionally are openly burned. When the shells are burned out in the open, they release CO2 and CH4 which contribute to global warming (Addo, H.O., 2017). When the shells are discarded improperly, they can increase pollution. The purpose of this project was to find a composition of waste materials, including plastic and coconut; that is effective as a building agent. Using recycled ingredients in unstabilized, compressed earth blocks (UCEBs) allowed the blocks to maintain strength and shape without the need of cement, while also ridding the Ghanian environment of pollution. Sustainable building material and UCEBs literature were reviewed to establish an understanding of the approach. The UCEBs that we created were made from a mix of water and soil. There was a total of four different compositions tested, with each composition presenting a different percent of plastic and coconut fiber as aggregates. Once the blocks were mixed and compressed, they dried for five days until they were ready for testing. The performed testing replicates the needs of the UCEBs in construction. The main tests performed were a shrinkage test, density test, flexural test, and erosion test.

The shrinkage test was to calculate the amount that the UCEBs shrink from when they are wet, to when they are dry. We measured the length of the UCEBs while wet and measured them again once they were fully dry. The difference in this number shows us the shrinkage. The density test showed the change in density between the freshly made, wet, UCEBs, and the dry UCEBs. The blocks were weighed and the change in density is calculated over time. The flexural test was to test the strength of the blocks. The blocks were topped with set weights to see how much they flex or if they break. The results were captured to see the strength of the blocks. Finally, an erosion test was performed to evaluate the amount of rainwater that the UCEBs could handle before they

began to erode. From the results of our experiments we can see that the mixture block performed the best in the strength test. This shows that more research is necessary into UCEBs with more than one waste material. Specifically, a project studying different compositions and matrices of coconut, plastic, dirt and water could present a practical substitution for current earth-based building practices.

Chapter 1. Renewable Resources in Building Construction

1. Introduction

Agricultural waste and plastic waste are prevalent throughout the world. Agricultural waste includes the plant waste left in the field after harvest. This plant waste totaled 5.5 billion tons in 2013 (Cherubin, 2018). Plastic waste is one of the most pressing environmental issues; the production of disposable plastic products is vastly overwhelming the world's structures to deal with plastic waste. Plastic waste is an even bigger problem in developing countries, primarily in Asia and Africa, where systems to collect plastic waste are often inefficient or nonexistent. Our project aims to reduce the impacts of agricultural and plastic waste by incorporating them in earth-based building blocks for construction in Ghana. In order to provide conclusions to the waste problem in Ghana, we researched current building materials and practices, as well as current waste product compositions and geographical/climate constraints. We also identified potential partners or processes for manufacturing such building materials that could be carried out in Ghana itself. In addition, we focused on processes that can be performed outside of a traditional laboratory setting. And finally, we built and tested preliminary building materials using waste products such as coconut fibers and plastics.

The purpose of our work is to explore the different options that Ghana has for sustainable blocks for building. Ghana has a large amount of plastic pollution; the Accra Metropolitan Assembly reports that 0.016–0.035 kg of plastic waste is generated every day per person, and at least 55% of that plastic waste remains in the waste stream (Kortei & Quansah, 2016). Ghana also is overwhelmed with coconut pollution which contributes to global warming through the increase of CO2 and CH4 into the environment (Obeng, et al., 2020). Coconut husks take over 10 years to decompose, leaving plastic and coconut waste a large problem for the country of Ghana. Since Ghana has a surplus of both plastic and coconut, this project seeks to solve the problem of waste and provide a sustainable alternative to current building practices. Further information and research is provided in the second chapter of our paper. Several important topics are discussed in this section necessary to gaining an understanding of the project. The literature reviewed in this portion of the paper laid the groundwork for the successful completion of the project. Specific topics such as waste management practices and codesign allowed the team to gain knowledge and insight.

In order to solve these problems, we conducted various tests to investigate the strength, erodibility, shrinkage, and density of the blocks. In the third chapter of our report we detail the methods of creation used during our project. Production of the blocks was relatively simple and is thoroughly recounted in the section. This section of the paper also contains how and what we tested the blocks. This portion of experimentation is also summarized in the third chapter of the paper. The necessary equations used to determine specific properties are in this section. Using the experimental information from the blocks, we analyzed the use of our blocks as a sustainable alternative to other building blocks in Ghana. The fourth chapter of our paper outlines the results of the project. The specific mechanical properties are detailed and discussed. Impact analysis, such as cost and social, are also discussed in the fourth chapter of the paper. The purpose of this review is to present the coconut and plastic waste UCEBs as a sustainable alternative for a strong building block. The MQP project presents how to make a UCEB, the composition of our blocks, the tests we performed on the blocks, and how each block performed in the test. In the conclusion of the paper we discuss the final results of the experiments and what this means for using coconut and plastic in UCEBs in the future.

Chapter 2. Background on Recycled Material Earth Construction

2. Introduction

In order to successfully carry out the project the team had to build an understanding on relevant topics. Gaining knowledge on material such as current practices in earth construction and waste helped to facilitate the completion of the project. This section will outline the information necessary to finish and understand the project. The topics discussed are earth-based construction, plastic waste, coconut waste, incorporating waste in earth blocks, and cross-cultural design.

2.1 Earth-based Construction

More than two billion people in the world live in earthen buildings (Y. Wang, 2015). Earth-based materials make up the main structural integrity of these buildings, mostly in Africa and Asia. Earth-based construction has many advantages; including that the material is fireproof, balances temperatures, and it is 50% to 60% cheaper than conventional cement-based construction (Adegun 2017). Earth-based construction is also environmentally friendly. Up to 30% less water is used in the production of earth blocks compared to conventional cement blocks (Oyelami, 2016). Earth materials are also recyclable, and clean to produce compared to conventional blocks which require fossil fuels (Abanda 2014). Further, unstabilized earth blocks are even more environmentally friendly than stabilized earth blocks. This is due to the lack of stabilizer in the block which cuts back on carbon emission. Figure 1 depicts a common example of earth construction in Ghana.

Figure 1: Earth Construction in Ghana

Despite the environmental and economic advantages, there is low interest in earth materials for housing construction. In Africa specifically, the number of earth-based housing is at an all time low. Of the 2.9 million housing units built between 1994 and 2009 in South Africa, only 17,000 were constructed using alternative or innovative systems such as earthen materials (Human Settlements Review, 2010). Recently built houses are made of bricks derived from imported materials and components (Mukiibi, 2011; Moosha and Moosha, 2012; Mercer, 2014). There are different reasons why there is low interest in earth-based construction. One reason is the attribution of earthen structures with poverty (Bosman et al., 2009). The main concerns are about earthen materials' durability and strength. In order for the earth blocks to be practical substitutes for conventional bricks, they must be able to have similar strength and durability results. In Africa, the changing of the climate presents difficulties with earth-based construction. Factors like rain or wind could erode the earthen materials that the homes are built out of. In response to this major drawback, chemical additives and binders like cement, bitumen, gypsum and lime are added into the soil mix to protect the brick from moisture decomposition and deterioration. Synthetic and natural materials such as straw, polystyrene, saw dust, wood pulp, coconut fibre, jute and rubber are usually added to stabilise earthen materials (Mant et al., 2015, Alam et al., 2015, Sharma et al., 2016). Synthetic materials may increase the cost of the blocks, eliminating the advantage of the low-cost materials. Using natural materials such as coconut fibers and plastic waste could keep the cost of the materials low, while increasing the strength and durability.

2.2 Plastic Waste

Plastics are synthetic polymers consisting of carbon atoms bonded together in long chains ("Science of Plastics", 2019). Due to their chemical structure they do not easily break down. Figure 1 shows a schematic of plastic's chemical structure. Many of the ubiquitous types of plastic have been chemically altered making them harder to reduce to smaller components. The prevalent types of plastics are not biodegradable and continue to accumulate in landfills. The decomposition time for one water bottle is 450 years (Kortei & Quansah, 2016).

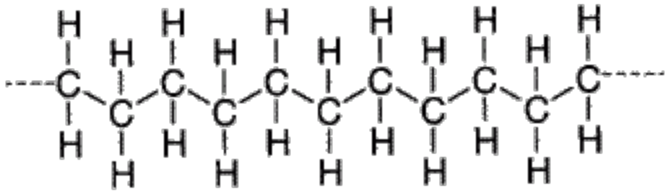


Figure 2: Chemical Structure of Plastic Polyethylene Polymer

Plastics are commonly found in the forms polyethylene or polypropylene. Polyethylene is used to make products such as water bottles, plastic bags, and kitchenware. In Ghana, the waste stream consists of 70% polyethylene (Kortei & Quansah, 2016). Polypropylene can be found in bottle caps and battery cases (British Plastics Federation, 2015). These kinds of plastics are categorized as single use plastics (SUP's). SUP's are plastics that have been created to be used once and then thrown away. These types of plastics are commonplace in the packaging industry. It is estimated that 80% of the plastic polluting oceans and coastlines are SUP's (Adam et al., 2020).

2.2.1 Rise of Plastic in Ghana

Ghana has seen a steady increase in plastic consumption over the last several decades. This is largely due to a shift in packaging of food and water. Food and beverages are often sold in high traffic areas in Ghana. Vendors sell items on sidewalks in open places like business districts. Prior to the popularity of plastic, food and water was packaged with cultural items such as leaf wrapper and brown papers. Following the discovery that food and water could transmit diseases, plastic packaging was considered to be more sanitary than traditional packaging. While plastic packaging alleviates food borne illness it leads to pollution. The packaging is often discarded onto sidewalks, gutters, and other unregulated dump areas. This leads to pollution in the drainage system in urban areas. Plastic accounts for 9% of pollutants in waste streams according to composition studies (Fobil & Hogarh, 2006). The Figure below shows plastic waste piling up in Ghana.

Figure 3: Plastic Waste in Ghana

One use of plastic packaging that has skyrocketed in Ghana is plastic water bottles. Population increases have surpassed efforts to bolster potable water services (Stoler, et al., 2012). Plastic water bottles have become the preferred method of water consumption. Many Ghanaians consider bottled water to be the “pure” form of drinking water. The uptake in plastic use combined with subpar recycling and waste management practices have led to an immense amount of plastic waste in Ghana (Quartey, et al., 2015).

2.2.3 Current Waste Management Practices

The Accra Metropolitan Assembly reports that 0.016–0.035 kg of plastic waste is generated every day per person. The estimated amount of plastic collected is 45%; the remaining 55% stays in the waste stream (Kortei & Quansah, 2016). Ghana uses landfills to remove their waste. The national waste management guidelines for Ghana declare waste should only be discarded in landfills, not unregulated sites (Addo, et al., 2017). As in many developing nations Ghana has an informal recycling system that accounts for almost one third of the waste collection (Quartey, et al., 2015). In 2014 Ghana introduced the Environmental Excise Tax Act 863 which taxes imported semi finished and raw plastic materials (Issahaku, et al., 2020). Ghanna, unlike many other Western African countries, does not have a ban on SUPs.

2.3 Coconut Waste

Coconuts are popular perennial fruits in Ghana. Vendors sell coconuts on the street in Ghana. There are many uses for several parts of the coconuts but the outer shells, or husks, are often piled up in streets. The husks can clog drains leading to rising mosquito populations. Figure 4 depicts large amounts of coconut waste accumulated in Ghana. The shells take a long time to decompose and occasionally are openly burned. When the shells are burned out in the open, they release CO2 and CH4 which contribute to global warming. When the shells are discarded improperly, they can increase pollution (Obeng, et al., 2020).

Figure 4: Piles of Coconut Waste

2.4 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 (Gairon 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.

In Ghana, research on incorporating natural fibers in compressed earth blocks (CEBs) has 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 our 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.

2.4.1 Plastic Waste in Earth Blocks

Earth materials are sustainable; however, they are lacking in areas like strength and damage resilience. CEBs are a contemporary use of earthen components. While they have better structural integrity than their predecessors, improvements are necessary to reach modern building standards (Donkor & Obonyo, 2020). The uptake in plastic waste in recent years has led to a rise in the use of plastic as an aggregate for building material. The use of recycled materials would reduce carbon footprints aiding in certain industries becoming more environmentally friendly (Arulrajah, et al., 2017). Several studies have been conducted investigating the use of plastic in earth building materials. Donker and Obonyo (2020) determined that plastic fibers added to CEBs had a positive impact on their mechanical properties. Using strips or fibers of plastic helps to ensure that the desirable properties are transferred to the CEBs (Arulrajah, et al., 2017). The addition of plastic fibers into CEBs could lead to a renewal in Earth construction.

2.4.2 Properties Affected by Recycled Aggregates

Properties that are important to our study include the density of the bricks, flexural strength, erodibility, and shrinkage. These properties are determined after testing the dried CEBs. With the introduction of recycled aggregates into the soil, CEBs become stronger in many ways. Without a binder or aggregates, CEBs are not up to modern building requirements. When studying CEBs with and without recycled aggregates, it was found that fibers connected by earth elements have been shown to possess better tensile stresses (Binici, et al., 2005). These fiber matrix's can also reduce shrinkage and increase shearing strength (Donkor & Obonyo, 2020). The introduction of layers of PE net increases the compressive strength of CEBs for both soils and compaction. The PE fibers improved ductility and post-crack performance of the blocks. Compressive strength of the CEB increased with the increased percentage of shredded plastic before decreasing. Blocks of over 7% shredded waste plastic could not be formed. Neither could soil samples with greater than 9.6 mm of shredded plastic (Akinwumi, et. al 2019). Compressive strength was found to be the highest when containing 1% of shredded plastic with a size of less than 6.3 mm. This compressive strength amounts to an increase of 244.4% when compared to a CEB containing no shredded plastic (Akinwumi, et. al 2019). According to the Turkish Standards Institution, the minimum compressive strength for unfired blocks should be 1 MPa. Therefore, the compressive strength of the CEB with no additive was lower than the CEB with shredded waste up to a certain point, then a progressive decrease was observed. In the Akinwumi study, only the CEB samples containing 1% shredded waste plastic satisfied the Turkish Standards Institution required minimum compressive strength of 1 MPa for an unfired clay brick.

Another property that is studied is erosion rate. The erosion rate experimentally increased with an increasing percentage of shredded plastic. For the CEB containing 7% of shredded waste plastic of particle sizes of less than 6.3 mm, the erosion rate increased by 389.8%, when compared with the erosion rate of the CEB containing no shredded waste plastic (Akinwumi, et. al 2019). These results indicate that the durability of the CEB decreased with the increasing percent of shredded waste plastic. From these results we can improve our study to ensure that the erosion rate decreases with an increase in shredded plastic.

2.4.3 Current Practices in Recycled Material Earth Blocks

There are many current practices for making recycled material earth blocks. Using recycled materials to reinforce the CEBs could be the future of sustainable building. At the Nelplast factory, plastic waste materials are shredded down to fine threads before being mixed with ordinary sand. Nelplast heats up the plastic to mix in with the earth material, and then compress the mixture to make CEBs. No binder is needed when mixing the plastic in this way and it removes the need for cement or lime in the blocks.

In the Akinwumi study, soil was obtained from Nigeria and passed through a sieve to create smaller lumps within the soil sample. Polyethylene terephthalate bottles were collected and crushed using an industrial crushing machine to different sizes. The soil was then mixed with varying percentages of waste plastic and mixed at optimum moisture content. The blocks were formed using a hydraulic compacting machine to produce the CEB (Akinwumi, et. al 2019).

CEBs with banana fibers are also being studied as a means for recycled material earth blocks. The mixture of the B-CEB includes clay, sand, aggregate, cement, banana fiber and water. These materials are mixed and compressed to form the reinforced blocks with randomly distributed natural banana fibers. Results showed that the same type of soil, compressed at different pressures, show that compression strength increases directly with the compaction pressure (Galindez, et al, 2009).

2.5 Cross-Cultural Design

In order for a successful project, the communities the project is intended for being involved is integral. Creating a project without using knowledge from the communities involved would be ignoring the important information they have. They have different expertise and wisdom that could ensure the project could be successfully implemented. For example, Nelson Boateng is already creating recycled earth blocks in Ghana and working with him to understand how he successfully started his business would be helpful to our project's success. Co-design would help alleviate issues that could arise from cultural differences. A solution that may work in Worcester may not be successful in Ghana.

Covid-19 made real, hands-on codesign extremely difficult. Had the project taken place in Ghana, the team could have worked alongside Ghanians to create a solution to the waste issue through UCEB's. For the most part co-design was limited to speaking with people with knowledge in Ghana. However, being able to communicate with Ghanaians, such as Academic City College, about our processes helped to reduce the amount of disparities due to cultural differences. The pandemic forced our project to be carried out in Worcester, meaning we had to use equipment available at our college. The ability to converse with Mr. Boateng helped to guarantee our project could be recreated in Ghana.

Co-design is essential to a successful project. The combination of the teams and Ghanaians' knowledge will help to create a project that is meaningful and long lasting. Speaking with people in Ghana is the best option since the project could not be done on the ground. These conversations will aid in creating a project that is actually useful in Ghana.

2.6 Conclusion

There are several aspects of the project that are not common in the United States. Earth-based construction is not prevalent in places such as Worsceter and therefore not often well understood. Understanding earth construction and the current practices is integral to creating a project that will be useful and successful. Plastic waste is an omnipresent issue in the world. However, there are several differences between plastic waste in Ghana and the United States. For example, Ghana has an informal waste collection system that has led to subpar waste removal. The team had to be knowledgeable about plastic waste in Ghana, especially in areas such as its decomposition. Coconut waste is not a common issue in climates not conducive with their growth. The information learned about the specific waste was important to understand the role they would play in the project. The current practices in recycled building materials was helpful to find a starting point and ideas for the project. There are Africans currently creating recycled building blocks using their own methods and materials. The team took an in depth look at their process' to gain understanding. Arguably the most important part of the project is the cross-cultural design aspect. This project was aimed for Ghanian communities and their involvement and input in the methods is imperative to success.

Chapter 3: Creating and Testing Waste Incorporated Blocks

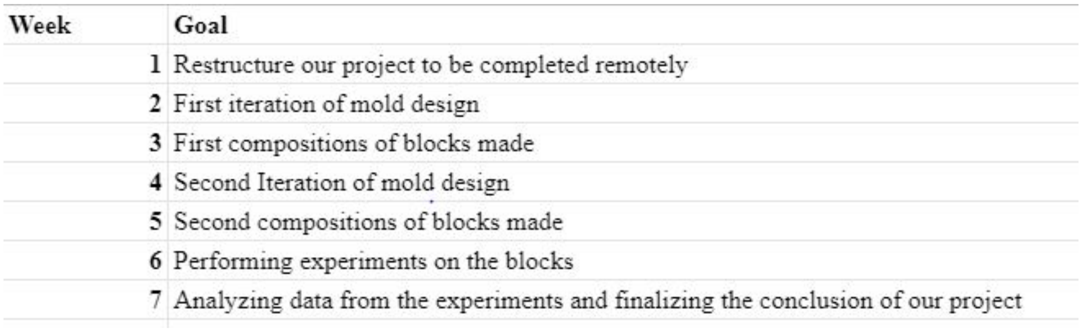
3. Introduction

Before beginning the experimentation elements of our project, we completed research to provide us with a foundational understanding of the numerous components within our project. In order to retain technical relevance and potential repeatability for applications in Ghana, it was essential that we modeled the methodology of our project without requiring pristine, sterile, expensive, technical laboratory equipment. Following the mentality of cross-cultural co-design, it was important to remember various equipment capabilities, resource characterization, expert knowledge, and ultimate desires from the project. We assumed the role as experts in mechanical engineering, while our collaborators (most critically Nelson Boateng from Nelplast) were experts in Ghanaian manufacturing, especially with earth as the foundational material.

While originally our project was intended to be carried out in Kyebi, Ghana, it was grounded in Worcester, MA, USA, due to the coronavirus. Additionally, due to elevated restrictions on the university operations, our project necessitated being reimagined in order to be at least partially completed outside of a formal laboratory setting. This new remote nature did have significant impacts on our project objectives, timeline, methodology, and co-design capabilities. However, these limitations resulted in a methodology that is likely more accessible and replicable in Ghana.

3.1 Project Activities and Scheduling

Our project timeline was seven weeks over the Winter of 2021. Figure 1 below outlines our timeline of preparing, creating, and analyzing our experiments with earth-based building bricks.



Week	Goal
1	Restructure our project to be completed remotely
2	First iteration of mold design
3	First compositions of blocks made
4	Second Iteration of mold design
5	Second compositions of blocks made
6	Performing experiments on the blocks
7	Analyzing data from the experiments and finalizing the conclusion of our project

Figure 5: Timeline

3.2 Production of Unstabilized Compressed Earth Blocks

The production of our compressed earth blocks was quite simple, so the process could be replicated anywhere in the world. Our study focused on the use of coconut fiber and plastic fiber as aggregates to the block. They are considered aggregates rather than stabilizers due to the lack of chemical binding agents such as cement or lime. Therefore, these blocks are considered unstablized compressed earth blocks. In order to create our blocks, we first had to design and build our mold. The mold was a handmade, wooden mold with wing screws to separate the mold for easy removal of the block. The mold was lined with wax paper to avoid friction disrupting the removal of the blocks. Figure 6 is an example of the mold being lined with wax paper.

Figure 6: Second Mold Iteration Lined with Wax Paper

The coconut fibers were ground up to a negligible dimension, and the plastic fibers were cut up into 4 cm x 2 cm strips. Then, the soil was sieved through a ¼ inch mesh and weighed to the nearest gram with a kitchen scale. Each block was made with approximately 428 grams of dry dirt. Using a weighted percent of 15.2% of dry soil, water was added to create an optimal moisture content of 15.2%. This moisture content was approximately 38 grams of water. At this point, the aggregates were uniformly distributed through the soil to present a better strength (Subramaniaprasad et al, 2014). The ground coconut fibers were mixed directly into the soil. For the coconut waste control block 1 gram of ground coconut fiber was mixed into the soil and water. After the mixture had been thoroughly combined it was placed inside the mold. The strips of PET plastic were placed directly into the mold as it was being filled. Half a gram of plastic waste was placed into the mold in layers. A layer of dirt was placed into the mold then half the strips of plastic were placed into the mold. Another layer of dirt was placed over the plastic followed by the rest of the dirt to create the plastic waste control block. For the coconut and plastic waste block 1 gram of coconut waste was mixed into the dirt. The process of layering the plastic strips was repeated to create the coconut and plastic mixture. Below, figure 7 depicts the mold being filled with dirt.

Figure 7: Dirt Being Added into Mold

We determined the amount of soil mixture through trial and error and density calculations. Once the mold was filled, a wooden block was placed on top of the mold and compressed with a hand-operated arbor press. The lower overall pressure and slower compaction rate of the compression are due to the fact that the arbor press was hand operated. If we had used a hydraulic press, there would have been more pressure overall and a faster compaction rate. A slower compaction rate from the arbor press may have slightly increased the density and flexural strength of the blocks, and lowered the erodibility of the blocks (Danso, 2016). Once the blocks were compressed, the wings screws were loosened, and the mold easily lifted off of the block. At this point the blocks were left to dry for five days until testing. Ideally these blocks would have dried out for longer, either 7-28 days in the sun, or two days in the oven. However, drying time was a limitation of this project due to the 7-week timeline.

3.2.1 Explanation for Testing Unstabilized Compressed Earth Blocks

The decision to test UCEBs considered time, material availability, ease of reproduction, sustainability, and relevance as the most important factors. Our team decided against CEB stabilizers such as cement or lime 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, our team aims to produce data that would be sustainable and reproducible in Ghana, or even beyond.

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. Figure 8 illustrates fired bricks.

Figure 8: Fired Bricks

They are made by mixing primarily clay and water (and can also include natural fiber aggregates), drying for seven 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 for our timeline and limited kiln availability. Additionally, it was difficult to determine the availability of clay 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

This study used the waste fiber composition of the blocks as its independent variable. These waste fibers were mixed in the soil of the UCEB's. A study conducted by Binici et al., 2003 determined that the ideal amount of waste fibers used as aggregates for UCEB's is between 0.1 and 0.2 percent by dry weight of plastic fiber and between 0.25 and 0.5 percent by dry weight of coconut fiber. Table 1 details the compositions of the blocks we created.

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

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

In order to gather more data points the arrangement of waste fibers could have differed, however based on findings by Binici et al., 2003 there was evidence that varying methods of fiber arrangements could have an impact on the properties of the blocks. Due to the timeline, it was decided that more than one independent variable would further complicate the project in a way that the timeline did not allow. Based on studies by Danso, 2015 and Donkor, 2014 it was decided that our project would investigate the composition due to tensile strength being improved by fiber aggregates.

3.3.1 Compressed Earth Blocks Mold Design

The mold was designed for ease of use and replicability. It was designed using low cost materials, namely wood. The original mold was four pieces of wood, two 6.5 x 3.5 x 1.5-inch pieces and two 8 x 3.5 x 1.5 inch pieces, screwed together to create a through hole. The lid was created using the dimensions of the through hole. Figures 9 and 10 show schematics and pictures of the first mold iteration.

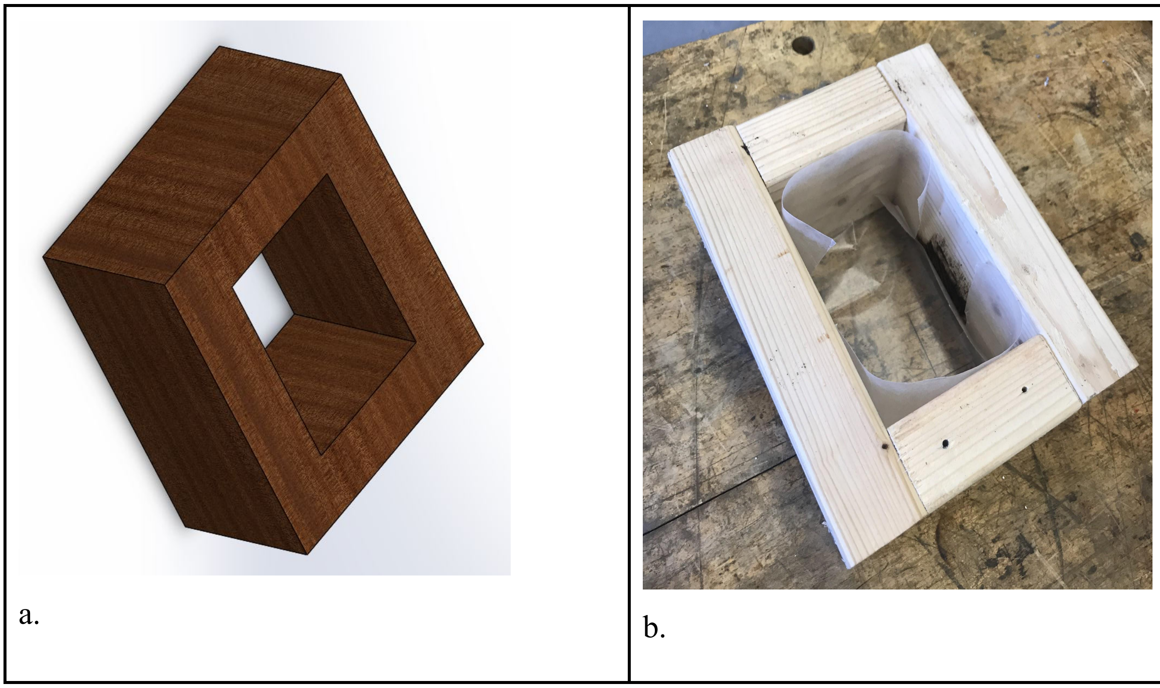


Figure 9: First mold (a) Solidworks design, and (b) completed fabrication, lined with wax paper.

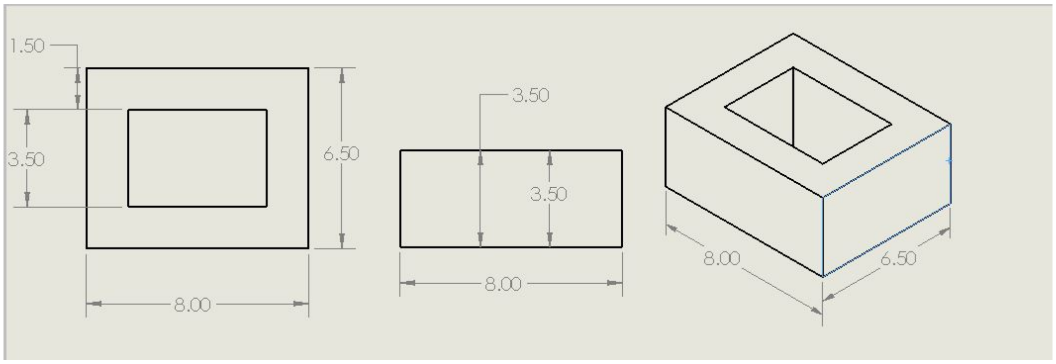


Figure 10: Dimensions of first mold.

The mold was lined with wax paper and filled with soil compositions and compressed with the arbor press. The mold was then placed on two pieces of wood that acted as stilts. The arbor press was then used to push the block out of the through hole. Figure 11 shows the first mold while being compressed with the arbor press.

Figure 11: Arbor Press Compressing Blocks

This mechanism of forcing the block out of the mold using the press created deformations in the blocks. A new mold was needed to create blocks without the cracks the original mold produced. Figure 12 shows the blocks created with the first mold iteration.

Figure 12: Block Made with First Mold Iteration

The second and final mold was designed using the same four aforementioned pieces of wood. Rather than being held together by screws this mold had two long bolts connecting the pieces of wood. The bolts had two butterfly screws on the end for easy removal. Pictured below in figure 13 is the second mold iteration.

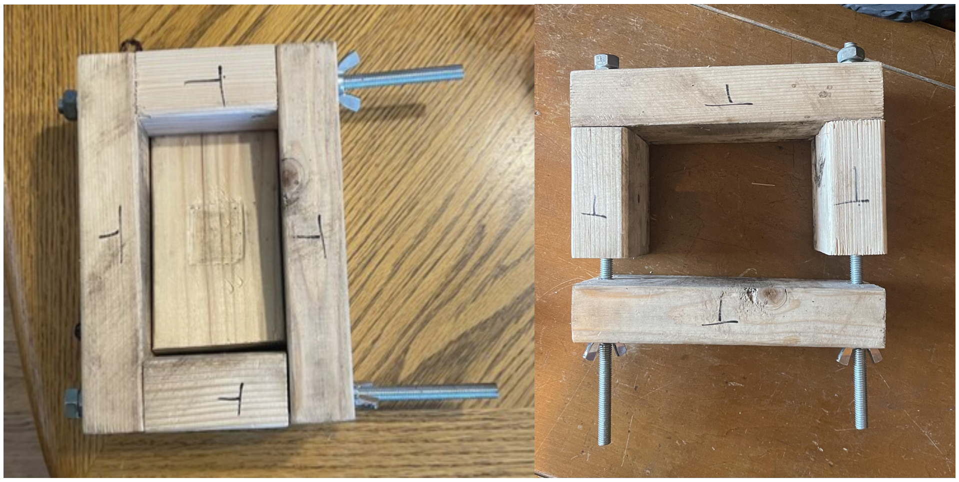


Figure 13: Second Mold Iteration

The mold was still lined with wax paper and filled with a specific amount of soil. Once the block was pressed the bolts could be unscrewed and the entire mold could be lifted off of the blocks. This removal process greatly diminished the cracks and deformations within the finished blocks.

3.3.2 Testing Unstabilized Compressed Earth Blocks Properties

The study looked at certain properties of UCEB's. These properties were UCEB density, erodibility, shrinkage, and flexural strength. These tests were conducted following a five day drying period for the blocks. In order to test the density, the blocks were weighed immediately after being removed from the mold and again after the five day drying period. The density increase was calculated by taking the average of the percent change from the control. Figure 14 shows the block undergoing the density test.

Figure 14: The Blocks During Density Test

The flexural strength was tested by placing the blocks on two planks of wood with an inch of the block on each plank and three inches hanging in the middle. Weight was added to the center of the block until the block failed. To calculate the maximum flexural strength the equation (flexural test max weight * 9.8066)/1000 was used. Figure 15 shows the blocks undergoing the flexural strength test.

Figure 15: Control Soil Block During Flexural Strength Test

For shrinkage, the blocks were measured immediately after being removed from the mold and then again following 5 days of drying time. Figure 16 portrays the blocks during the shrinkage test.

Figure 16: Block During Shrinkage Test

To test the erodibility, the blocks were placed under a constant drip for 25 minutes and the cavity in the block was measured.

3.4 Conclusion

The methodology of our project was intended to be easily replicable. The materials and methods were chosen for their simplicity as well as their efficiency. In order for the project to be successfully implemented in Ghana, it has to be repeatable. The materials used such as dirt, water, waste and wood are all commonly available. The use of the Arbor press was chosen based on available equipment. Due to the project being completed in Worcester the team had to work in a university lab rather than the actual Ghanian communities.

Chapter 4. Analysis of Blocks

4. Introduction

The project was intended to be completed in Ghana to provide a possible solution to waste pollution. The team examined the impact that the project could have on Ghanaian communities. After the completion of the blocks and their testing the team took an in depth at their properties. Analyzing the blocks helped to determine if the blocks could be used in earth construction. Limitations faced by our projects were abundant. In the section below the team outlines the various limitations of our project

4.2 Impact Analysis

A key aspect of our project is to ensure that the project is replicable in Ghana. One important factor in this is the cost of making the bricks. In order to have these blocks as a feasible alternative to cement blocks, they must be low cost and easy to replicate. Our blocks would not include any materials that must be imported to Ghana. For this reason, we cut out cement and other stabilizers that are not naturally found in Ghana. Without the cost of importation, we were able to keep the production cost of the blocks extremely low. The cost analysis of each individual UCEB is illustrated in the table below. Our cost included the cost of wood for the mold, potting soil, and coconuts from the grocery store. If this project were to be replicated in Ghana, soil and coconuts would not have to be purchased, as these are available in the environment of Ghana. The plastic also comes from already used plastic water bottles, so there is no cost involved in retrieving the plastic for the UCEBs. Table 2 outlines the costs associated with creating the blocks.

Material	Cost	Cost per Unit
Wood	$6.25 (2x4x8)	One time Cost
Wing Screws	$3.00	One time Cost
Soil	$9.99	$0.25
Coconuts	$3.99	$0.01
Plastic	0	0
Water	0	0
Wax Paper	$3	One time Cost
Total:	$26.25	$0.26

Table 2: Cost of blocks

Removing the cost of the soil and coconuts, each block would have virtually no cost. There is a one-time cost of $12.25 to make the mold. After this cost, it would be free to make the blocks because all of the materials are available in nature. The aggregates of coconut and plastic will be free because they will be reused from the waste in Ghana. The cost of one brick in the US is approximately $0.50. The average house in Ghana is 1,200 sq ft, there are 7 average bricks used per square foot (Chen, 2017). The average house will need about 8,176 bricks to complete, the cost of which would be over $4,000. In the price of blocks alone the user would save over $4,000 using our sustainable blocks rather than bricks.

4.2.2 Social Impact

A main focus of our project was to create a process and deliverable that could be reproduced in Ghana with relative ease. The four components of our blocks soil, water, coconut, and plastic are readily available materials in Ghana. The mold is created using wood and bolts which are relatively low-cost materials. The ability of our project to be recreated inexpensively could have a positive impact on low cost housing. If the blocks prove successful, the opportunity for housing to be built with the low-cost materials could be great. Building houses, even with earth construction, can be extremely expensive. Giving people the chance to build or buy their own home would change lives. Our project did not heat up any plastics that would create pollution meaning our blocks could be made without hurting the environment. Perhaps the greatest social impact is the potential to add value to waste. If the blocks are successfully implemented in Earth construction the large amounts of plastic and coconut waste littering the country could be used. This could significantly reduce the amount of waste needing to be cleaned alleviating a major issue in Ghana due to the informal collection of waste. The success of these blocks could help furthermore sustainable practices in the country. For example, the blocks could be used in the building of micro flush toilets which aim to alleviate pollution in Ghana. They could also inspire others to use waste in recycling and sustainable practices. The creation and selling of the blocks could lead to business opportunities for local Ghanians. This could mean that waste could earn people money, making waste valuable.

4.3 Properties of CEBs

Following the completion of block analysis, we calculated the block properties. There were several noticeable differences in the properties based on compositions. The block containing no waste performed significantly worse in almost all categories. The waste reinforced blocks performing better may be an indication they would be successful in use in earth construction. The block with no waste failed before weight was even placed on it during the flexural strength test. The coconut and plastic blocks failed after 5.8 N and 10.05 N, respectively. The mixture block failed at 11.9 N. Blocks used in earth construction need to have a specific maximum flexural load. The capability of our CEB's to withstand certain loads is important to the success of the implementation of the blocks in real world applications. The success of the blocks in these specific properties is imperative. More blocks of varying compositions could determine if differing amounts of waste affects the maximum flexural load capability. The erosion rate is important because the test is made to imitate driving rain. The blocks can't erode away during rain as it will jeopardize structural integrity. The mixture block eroded at the fastest rate. The creation of more blocks would have allowed for more erosion rate tests to be carried out to determine if the mixture could be changed in order to make blocks with a slower rate of erosion. Below, table 13 outlines the results we found after we completed the testing of the blocks.

Composition	Max Flexural Load (N)	Erosion Rate (mm/min)	Density Increase (%)
No Waste	0	0.245	0
Plastic	10.05	0.508	3.24
Coconut	5.8	0.508	4.91
Mixture	11.9	0.762	1.58

Table 3: Cost of blocks

4.4 Comparison to Store Bought Bricks

Following the testing of our earth blocks, we tested three additional store bought bricks to compare their properties. We could not perform the density increase of the bricks since we only received them once they were completed. The bricks we tested were Luna 6.02 in. L x 4.33 in. W x 2.36 in. H North Creek Blend Concrete Paver, Holland 7.75 in. x 4 in. x 1.75 in. Fieldstone Concrete Paver and a 8 in. x 4 in. x 1.75 in. Red/Charcoal Concrete Holland Paver. Each brick was made from dry-cast concrete. There were several limitations to testing these store-bought bricks. Most importantly, we performed these tests from home, and do not have access to

Figure 17: Store Bought Bricks Undergoing Testing

equipment that can accurately test the flexural strength of the bricks. Figure 17 depicts the bricks purchased at a store undergoing testing. The dry-cast concrete bricks are considerably stronger than our earth based blocks. The bricks did not fail under any of the weights we tested. However, we only could test up to 50 lbs of force on the bricks. The bricks did not fail under our tests however the maximum load that the bricks could take is unknown because we were not able to test for more than 50 lbs. The other test that was performed was the erosion test. For the erosion test the bricks are placed under a steady drip of water for 30 minutes. After 30 minutes, the impression left by the water is measured to determine the erosion of the brick. Compared to our earth based blocks, the bricks had considerably less erosion. There was no visible impression left by the water on the bricks. Therefore, the store bought bricks outperformed the earth blocks in both tests.

4.4 Limitations to Testing CEBs

Limitations in our project include co-design, control, specification, and time. Projects through the Project Center at WPI are always completed with co-design to ensure that the project is specifically applicable to the problem of the client or stakeholders. Since we could not perform our project in Ghana, this made co-design near impossible. We contacted two Ghana academics and one entrepreneur who are all working on similar waste incorporated building materials. to help our research, however these stakeholders did not have a direct hand in our project. Without co-design, it is possible that the outcome of our project is not what Ghana needed, since we have never been to Ghana and we are only using our research to look into potential solutions.

Another limitation of our work is the low number of data points; we only have two data points for each composition. This introduces the possibility of control limitations. Since there are two data points, variables may be different between these two data points due to human error. Our data is not statistically relevant, so our data points may be outliers. Therefore, if more blocks were made then the results may have been different.

Originality of our work also proved limiting, since a project such as ours had never been explored before, it was difficult to find research that would lend itself to our project. The originality of our work comes from not using any stabilizer, and using two waste products instead of one. There are similar experiments with blocks that include stabilizers such as cement or heated plastic, and have one waste product such as plastic or banana waste. Using both coconut and unheated plastic was a limitation to our project due to the originality of the concept. Our design intention to avoid cement or other stabilizers did limit the strength of our blocks, but that was informed by our assumption that imported materials would reduce the overall sustainability of our project and would conflict with our timeline. This allowed us to keep the cost of the project extremely low. By not using any imported goods, we could not use a stabilizer such as cement. This greatly reduced the strength of the blocks; however, this also helped our timeline. If we had used stabilizers in our blocks then there would be not enough time to test the blocks within our 7 week time frame. Using the assumption of not incorporating cement or any stabilizers diminished the strength and integrity of our block, so this was a limiting factor in our testing.

Our seven week timeline introduced limitations into our project. As a result of the timeline, we decided on unstabilized blocks, which are less strong but they have no cure time. This allowed us to make and test the blocks within our given timeframe. However, we sacrificed overall strength for this timeline. There is no infrastructure or current practice of making CEBs in the US, so we had to do more iterative design of the process itself than we originally hoped we would. This took more of our time than we accounted for, and we were unable to make as many bricks as a result. Our process is also not replicable at a large scale. We made every block by hand, and did not explore designs involving large scale production. The lack of time and global pandemic limited our access to lab equipment, and the opportunity to complete this project in Ghana. If we had the ability to complete this project in Ghana, we would have had the access to let the blocks dry for long periods of time in the hot Ghanian sun outside. Instead, we made our blocks in the labs in Worcester and some blocks broke during transit. In addition, we had to use plastic, coconuts, and soil from the US, which might have significantly different properties from Ghanian plastic, coconuts, and soil. We did not account for this in our experiments, as there is no information about the characteristics of Ghanian soil. As a result of the ongoing COVID pandemic, part of the project had to be reimagined completely, and our intention was to make our process completely replicable outside of a lab environment. For this reason, we chose not to melt plastic, and have less accurate lab equipment. For example, we used a kitchen scale with all weight rounded to a whole gram. This is relevant to what it would have been like to perform these processes in Ghana, however we sacrifice the technical relevance of our data. Due to our restrictions, we produced a very low number of testable blocks meaning that our results are not statistically relevant.

4.5 Conclusion

The mold design took more than one iteration, but the second iteration allowed us to create earth blocks easily. This mold iteration also produced blocks without deformations unlike the previous iterations. Cost analysis is an important aspect of our project. In order for the project to be easily replicated the costs needed to remain relatively low. For example, some of the materials used are easily available and in the case of the waste are free. Taking a look at the social impact of the project allowed the team to consider the positive effects. Low cost materials for earth construction could allow for opportunities such as affordable housing. The incorporation of waste into sustainable processes' can also help alleviate the pollution in Ghana. Analysis of the blocks properties was to investigate how well the blocks could potentially perform in earth construction. This is important for the future of this project to continue looking at waste incorporated blocks. Further research into the properties of the blocks would be useful to determine their efficacy. The limitations faced by our project such as the timeline and Covid-19 meant that the team often had to adapt and change. Some aspects also had to be changed in order to accommodate the several changes. However, the project was still able to be successfully completed even with the many limitations.

Chapter 5: Recommendations and Conclusion

5. Introduction

After the completion of our project our team considered the many ways in which the project could be continued. One way is for another team of WPI students to progress the research conducted by our team. A WPI team on the ground in Ghana could also carry on the project in ways that our team was unable to. Another way to extend the project work is by Ghanaian people. Further research by people in Ghana could help to gain more knowledge about the waste incorporated earth blocks.

5.1 Recommendation for Future Projects

We recommended further research be done in this area in order to provide a solution to sustainable UCEBs. Many research in these areas already exist, however our project sought to use plastic and coconut fibers as an aggregate in our UCEBs. In other CEBs, the plastic is heated before it is incorporated into the blocks, and other CEBs do not use coconut waste as an aggregate. In addition, earth blocks are usually made with only one added material. Our project studied the effect of using two aggregates to strengthen the earth blocks. More data points with these two variable differences are recommended. In our project we relied on two data points for each composition of the block. This introduces room for human error to have affected our testing. In our testing we had several iterations of a mold design, the final iteration is what we would recommend in future projects. The mold included 11 inch bolts to release the mold to easily retrieve the blocks. Our blocks performed well in our series of tests, however more tests must be performed to see the blocks' capability to perform in the place of other blocks such as concrete or other sustainable CEBs. Specifically, the mixture composition performed the best in the flexural strength tests. This composition presents the most benefits, however it is still susceptible to erosion. Further research into using both coconut and plastic as aggregates is necessary to prove that our UCEBs are a valid substitute for other current building blocks.

5.2 Recommendation for Ghanaians

There are several Western African variations of recycled earth building materials currently in use. However, almost all of these include heating plastic which causes pollution. More research into the feasibility of plastic strips used in earth building materials could have a positive impact on the already valuable recycled material industry. Further research into coconut fibers as an aggregate for building materials could provide a solution to the growing issue of coconut litter.

5.3 Conclusion

The results of the block analysis indicate that the fiber aggregates have a positive impact on the properties needed for a successful implementation of the UCEB's into earth construction. Further research into the effect of the block fiber composition on the properties is needed to determine the optimal fiber quantity. If our project had a longer timeline we could have created more blocks to consider the optimal waste fiber amount. Another area we could have looked at was how the waste was incorporated. Different methods of incorporation could have an effect on the block's properties. Our results were a preliminary look at recycled building blocks. A WPI or Ghanian team could take our results and dive further into the different ways to manipulate the blocks properties. Conducting a project continuing the research on the ground in Ghana would also allow a team to inspect if soil will play a role in the block's properties. Another project could also focus on a way to create these blocks in Ghana without using the lab equipment such as the Arbor Press. The implications of Covid-19 impacted our project in several ways and adapted to allow for its execution in Worcester, not Ghana which led to our project being completed differently than originally intended.

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