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BENEFICIAL REUSE OF LOCALLY-AVAILABLE WASTE MATERIALS AS LIGHTWEIGHT AGGREGATE IN LIGHTWEIGHT CONCRETE

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BENEFICIAL REUSE OF LOCALLY-AVAILABLE WASTE MATERIALS AS
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Abstract

This study investigated the physical characteristics of lightweight concrete produced using waste materials as coarse aggregate. The study was inspired by the author's Peace Corps service in Kilwa, Tanzania. Coconut shell, sisal fiber, and PET plastic were chosen as the test waste products due to their abundance in the area. Two mixes were produced for each waste product and the mix proportions designed for resulting compressive strengths of 3000 and 5000 psi. The proportions were selected based on guidelines for lightweight concrete from the American Concrete Institute. In preparation for mixing, coconut shells were crushed into aggregate no larger than 3/4 inch, sisal fiber was cut into pieces no longer than 3/8 inch, and PET plastic was shredded into 1/4 inch-wide strips no longer than 6 inches. Replicate samples were mixed and then cured for 28 days before they were tested for compressive strength, unit weight, and absorption. The resulting data were compared to ASTM Standards for lightweight concrete masonry units to determine their adequacy. Based on these results, there is potential for coconut shell to be used as coarse aggregate in lightweight concrete. Sisal fiber was unsuccessful in producing the appropriate compressive strength. However, the reduction in spalling of the hardened concrete and the induction of air in the mixes incorporating sisal fiber suggests that it has the potential to improve other characteristics of lightweight concrete. Concrete mixes using PET plastic as aggregate resulted in adequate compressive strengths, but were too dense to be considered 'lightweight' concrete. With some adjustments to slightly decrease absorption and unit weight, the PET plastic concrete mixes could be

classified as medium weight concrete and, therefore, achieve many of the same

benefits as would be seen with lightweight concrete.

1.0 Introduction

Concrete is used world-wide as a building material twice as much as all other building materials combined (EcoSmart Concrete, 2014). Therefore, it is no surprise that concrete is typically the desired material for construction in Tanzania, both for housing and for school buildings. The transition in Tanzania to construction using mortared concrete masonry units (CMUs) from the traditional use of mud and wood has resulted in longer-lasting, more durable buildings (Ekolu 2006). However, the current form of concrete used also results in labor-intensive practices and is expensive, which may limit access to other resources in financially-challenged communities.

In developing countries, building materials are frequently the largest expense of housing construction, often making up 70% of total costs (Erguden 2001). In the case of mortared CMU construction in Tanzania, the cement is typically imported from other countries, while the rest of the materials are transported from distant cities. Laborers are hired for projects and their efficiency directly affects the time and cost of those projects. According to a study sponsored by the National Concrete Masonry Association and the Expanded Shale, Clay & Slate Institute, "as weight increases, production decreases" due to the strain it puts on laborers (Lochonic 2003). The same study also found that "lightweight units increase production over

heavyweight units." In addition to increasing production, lightweight units also decrease on-site injuries.

One approach for reducing the weight of concrete blocks is to use lightweight concrete. Lightweight concrete is defined as weighing less than 105 pounds per cubic foot (ASTM C90 2012). This characteristic is typically achieved due to the nature of the aggregate used in lightweight concrete mixes. Lightweight concrete can be made using all lightweight aggregate or a combination of light and normal weight aggregate. The weight requirement set forth by ASTM is considerably less for lightweight concrete when compared to normal weight concrete, which is defined as being more than 125 pounds per cubic foot (Lochonic 2003). In addition to the benefits reduced block weight could have for the laborers and project timelines in Tanzania, lightweight concrete also requires less material than normal weight concrete. The latter has the potential to decrease the amount of material that must be imported. Currently, of the materials used to produce building materials in Tanzania, only about 47% are locally available (Sabai et al., 2011 and references therein). In addition to the weight and material benefits of lightweight concrete, studies have shown that it also has better thermal insulation and noise absorbing properties than normal weight concrete (Gunasekaran 2011).

Interestingly, the use of lightweight aggregate concrete has a long history. For example, it was used in the construction of the Pantheon and the Colosseum in Rome

over 2000 years ago (Berntsson and Satish 2003). Lightweight aggregate can be categorized into three categories: naturally occurring, manufactured, and naturally occurring then processed (Shafigh et al. 2010). Initially, the lightweight aggregate used typically fell into the 'naturally occurring' category and included volcanic materials like pumice and scoria, but as the availability of these materials became more limited, 'naturally occurring and processed' aggregate such as shale, slate, and clay began to be used as aggregate (Berntsson and Satish 2003). As demand continued to increase, new technologies were developed to discover and apply manufactured materials as lightweight aggregate. This has included materials such as fly ash, colliery waste, and blast furnace slag (Shafigh et al. 2010). Due to its promising qualities, the use of lightweight concrete and various forms of lightweight aggregate have only increased worldwide over time. However, for the use of lightweight concrete to be economically viable in developing countries, it is necessary to identify contextually-based materials that can be used as lightweight aggregate.

In Tanzania, there are several readily available materials that potentially could be used as lightweight aggregates. For example, on the eastern coast of Tanzania, coconut shells and Polyethylene terephthalate (PET) water bottles are abundant; both decompose slowly. Coconut is used daily by most inhabitants in their cooking, but there is currently little use for the shells. In many tropical countries, coconut shells

are among the most common agricultural solid wastes (Gunasekaran et al. 2011). This not only adds to the accumulation on the ground of solid wastes, but can also serve as breeding grounds for mosquitos that spread diseases like malaria and dengue fever after it rains. Currently, coconut shells are used as a raw material for activated carbon production, and for decoration but little else (Olanipetun et al. 2006). With 93 countries producing coconuts, an overabundance of waste is created every year with nowhere for the slow-to-degrade material to go. It has been found that coconut shells can be used in concrete as lightweight aggregate and can thereby aid in producing the strengths required even for structural concrete (Olanipetun et al. 2006). According to a study performed by Kaur and Kaur (2010), after 28 days, plain concrete mixed with coconut shell aggregate showed high enough strength to meet the required values. It has also been found that, due to the smooth surface on one side of coconut shells, the workability of coconut shell aggregate concrete increases (Gunasekaran et al. 2012). Although studies have indicated a decrease in strength with an increased percentage of coconut shell as aggregate, strengths have been seen to continue to increase even after 365 days. This indicates that the coconut shells do not deteriorate when in the concrete matrix (Gunasekaran et al. 2012), and that mixes could be designed to meet the required strengths in various applications.

Another material that could potentially be used as lightweight aggregate is plastic waste, which accumulates as a solid waste in Tanzanian communities even faster

than coconut shells. As of 2001, the amount of plastic consumed around the world increased to 100 million tons, with PET plastic making up the 2nd largest fraction of the total plastics waste stream (Siddique et al. 2008). Even in the U.S., of all plastic waste, only seven percent is being recycled (EPA 2003). This waste is extremely harmful to the environment as well as human beings. For example, harmful chemicals can be released from the waste, like metal antimony, which can leach into water sources. Also, in the case of burning of plastic waste, which happens frequently in Tanzania, metal antimony can be released into the air (Science Daily 2011). The inhalation of antimony on a long-term basis could potentially lead to inflammation of the lungs, chronic bronchitis, and chronic emphysema (EPA 2013). While PET plastic is already being recycled to be used in things like fence posts and carpets, the benefits of using it in concrete include an increased reduction in landfill waste and, as a building material, an alternative to pressure-treated lumber that can leach chemicals into water (Siddique et al. 2008). Studies have been performed on all types of plastic for use as fillers in materials like concrete, and it has been found that the chemical composition of the plastic is not generally significant in compatibility (Siddique et al. 2008). This, combined with the low density of PET plastic, makes it a good candidate for the replacement of expensive aggregate, while also potentially decreasing the dead weight of structures. In addition, using PET plastic as a lightweight aggregate would provide a more cost effective way of recycling materials. As it is, recycling options like melting fusion

to reform PET plastic into new water bottles induce costs that prevent it from being a viable option (Choi et al. 2005). While studies frequently show that an increase in PET plastic in concrete leads to a decrease in compressive strength, in a study performed by Choi et al. (2005) on PET plastic in the form of granules (upper limit 5mm), it was found that replacing fine aggregate with less than 50% PET did not affect the compressive nor the flexural strength. These results indicate there is potential for this material as a lightweight aggregate.

Finally, sisal fiber is another readily available material in Tanzania, with potential for use as a lightweight aggregate. Sisal grows easily throughout the year in Tanzania without fertilizers or pesticides (FAO 2009) and, over the course of its lifetime, absorbs more carbon dioxide than it produces (FAO 2009). After the fibers are harvested, the rest of the plant can be used to produce bioenergy, animal feed, and fertilizer (FAO 2009), making it an ideal material for use in construction. In addition to its more common use in twine and sacks, sisal fiber is increasingly being used as a component for a plethora of end products, including automotive components, brake pads, furniture, filters, and carpets (FAO 2009). Research on its capabilities as reinforcement in concrete and mortar is ongoing and has shown promise (Toledo Filho 1999). Of vegetable fibers, sisal has been identified as the strongest, and when proportioned and mixed properly with the compatible materials, it can increase the flexural strength, impact strength, and post-cracking behavior of

concrete (Toledo Filho, 1999). Tanzania is among the highest sisal fiber producers in the world with half of the country's supply being exported for use in other countries (FAO 2014).

The use of coconut shells, waste plastic, and sisal fibers as lightweight aggregate in lightweight concrete has the potential to be beneficial environmentally, financially, and physically for the people of Tanzania. The next chapter outlines the scope and objectives of this study for evaluating this potential application. Subsequent chapters describe the project site and experimental materials and methods, followed by a presentation and discussion of the results obtained in this experimental study. Finally, the report conclusions and recommendations for future work are provided.

2.0 Scope and Objectives

2.1 Project Motivation

The initial motivation for this research came from my time as a Peace Corps Education Volunteer in Kilwa, Lindi, Tanzania. In Kilwa, I taught at Ilulu Girls' Secondary School for two years. Throughout my time there, I witnessed and experienced the obstacles teachers and students face due to a lack of resources and funding. For example, I was told on multiple occasions that there were not enough beds, desks, or chairs for the students to use. At the same time, I observed a seemingly unnecessary amount of money and energy go into the construction of classrooms and dormitories. Ironically, even as available funds are being exhausted to purchase and import construction materials into the area, there is a significant amount of solid waste litter the ground in the community that could potentially be used to replace some of the harmful and expensive construction materials being transported to Kilwa over long distances.

2.2 Goals and Objectives

The overall goal of this study was to provide a better option for Tanzanians constructing buildings with CMUs by investigating the beneficial reuse of what are now considered solid wastes as construction materials. Hopefully, by replacing formerly imported construction materials with locally-available waste materials, the

cost of school and dormitory construction could be reduced, and more funds would

be available for equipping those facilities and serving the students. Specifically, this

study examined the potential for using coconut shells, shredded PET water bottle

plastic, and sisal fibers as lightweight aggregate in lightweight concrete.

There are two primary objectives for this study:

1. Prepare lightweight concrete mixes using coconut shells, shredded PET water

    bottle plastic, and sisal fiber as lightweight aggregate.

2. Compare the relevant characteristics of lightweight concrete mixes using

    coconut shells, shredded PET plastic, and sisal fiber, to those of the

    appropriate ASTM Standards. Characteristics used for comparison were air

    content, density, compressive strength, and water absorption.

3.0 Project Site

Tanzania is a country located in East Africa on the shore of the Indian Ocean and surrounded by Kenya, Malawi, and Mozambique (Figure 3.1). It has a population of approximately 46,218,000 and is approximately 945,087 sq.km., including three coastal islands (United Nations 2014). The climate varies drastically from the tropical plains of the coast to the temperate highlands of the North and South, as does the topography with elevations ranging from sea level to Mt. Kilimanjaro, the highest point on the continent, at 5,895 km (CIA 2014).

The Kilwa District is located along the tropical coast in the Lindi region, approximately 320 km south of Dar es Salaam, the country's largest and most important city. Temperatures in the Kilwa District are typically between 22ºC and 30ºC. The district is approximately 13,347.5 sq. km (Lindi 2007) with a population of 190,744 people (Geohive 2014). The district's original wealth came from trade through the port at Kilwa Masoko. Today, typical means of livelihood are crop production, goats, poultry, and fishing, resulting in average annual earnings of 150,000 shillings per capita or approximately $100 US. Popular crops include cashew nuts, coconuts, and sisal grown as cash crops and maize, cassava, and rice typically grown as staple crops.

Figure 3.1 A Map of Tanzania

(http://ian.macky.net/pat/map/tz/tz_blk.gif/)

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Ilulu Girls Secondary School is a boarding school located within the Kilwa District in the village of Njia Nne. The school consists of 16 buildings, with 500 female students ranging from 13 to 17 years in age. Students are on campus for the entire year with the exception of December and June. National exams are conducted for students in their second and fourth years during the month of November. Approximately twelve teachers, three guards, and two cooks are on site year-round with student teachers arriving for six-week intervals at the beginning and end of the school year.

Of the 16 buildings on the Ilulu Girls School campus, one is currently under construction. Like the buildings at most other schools in Tanzania, this new structure is being constructed from CMUs formed in a mechanical block press. The materials for the CMUs and mortar are combined in pits formed on the ground by manual laborers with shovels. The mix for the CMUs consists of sand, water, and cement. According to Sabai et al. (2011), typical water to cement ratios used in Tanzania for concrete blocks range from 23% to 30% by weight, while typical cement to aggregate ratios range from 1:7 to 1:14 by volume. On site in Kilwa, the cement to aggregate ratio was approximately 1:9. All of the materials are purchased elsewhere and transported to the site. Cement and aggregate are transported by truck and water is piped in from the village. After CMUs are formed with a manual or mechanical block press, they are set in the sun to cure until dry. During the construction process,

CMUs are laid width-wise and mortared together. All work is manual and, therefore, both time-consuming and labor intensive, due to the weight of the CMUs.

Importantly, Sabai et al. (2011) report that only about 20% of Tanzanian building contractors perform laboratory-based quality testing of their concrete block. The remaining roughly 80% instead report that they use simple on-site tests. Three on-site test methods are common. In one method, a concrete block is lifted up and dropped down to the ground. The expectation is that a strong block will only break into two pieces, while inferior blocks will disintegrate into more pieces and not be used. A second test method is based on the scratching of the block surface using fingers. If the block surface erodes easily, it is not used. Finally, in the third test, the block is cut with an axe. In this test, if the block breaks easily, it is disqualified. Clearly, the results of these on-site test methods are a function of the tester's power and energy, and whether the surface used for dropping the blocks is hard or soft. As a result, these methods are unreliable for concrete block control quality.

4.0 Experimental Materials and Methods

To achieve the overall project goal of reducing the need for imported aggregates in concrete masonry units by replacing them with lightweight aggregate in the form of waste products (coconut shells, shredded plastic water bottles, and sisal fiber) used with normal weight fine aggregate (sand), the experimental mix designs were chosen from ACI 211.2-98 *Standard Practice for Selecting Proportions for Structural Lightweight Concrete* Method 1 (American Concrete Institute 2004). The mix designs were also checked for compliance with ASTM C90 *Standard Specification for Loadbearing Concrete Masonry Units* (ASTM 2012) and ASTM C331 *Standard Specification for Lightweight Aggregates for Concrete Masonry Units* (ASTM 2010). The details of this experimental approach are described below.

4.1 Materials

The fine aggregate used in this study was glacial sand from Hancock, Michigan. Three different waste materials were chosen to replace coarse aggregate in the lightweight concrete: crushed coconut shell, shredded water bottle plastic, and sisal fiber twine. These materials were selected because they are readily available in Tanzania, whereas conventional lightweight aggregates are scarce and costly. The coconut shells were crushed using a wood mallet, and sieved to pass through a 3/4 inch sieve before use. Polyethylene terephthalate (PET) plastic water bottles were shredded with a Fellowes PS70-2CD shredder to a width of 1/4 inch and cut into

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lengths no longer than 6 inches. The sisal fiber was purchased in the form of rope and cut into pieces 3/8 inch in length, which released individual fibers.

A sieve analysis was performed on the coconut shells and fine aggregate, the results of which are summarized in Figure 4.1 and 4.2. Using the results of the fine aggregate sieve analysis, a fineness modulus of 3.22 was calculated, indicating that the aggregate was relatively coarse for a fine aggregate. As discussed below, this value was used to approximate the necessary volume of coarse aggregate needed for each mix as per the standard method of proportioning (American Concrete Institute 2004). The shape and weight of the PET plastic and sisal fiber particles used in this study prevented a sieve analysis from being applicable.
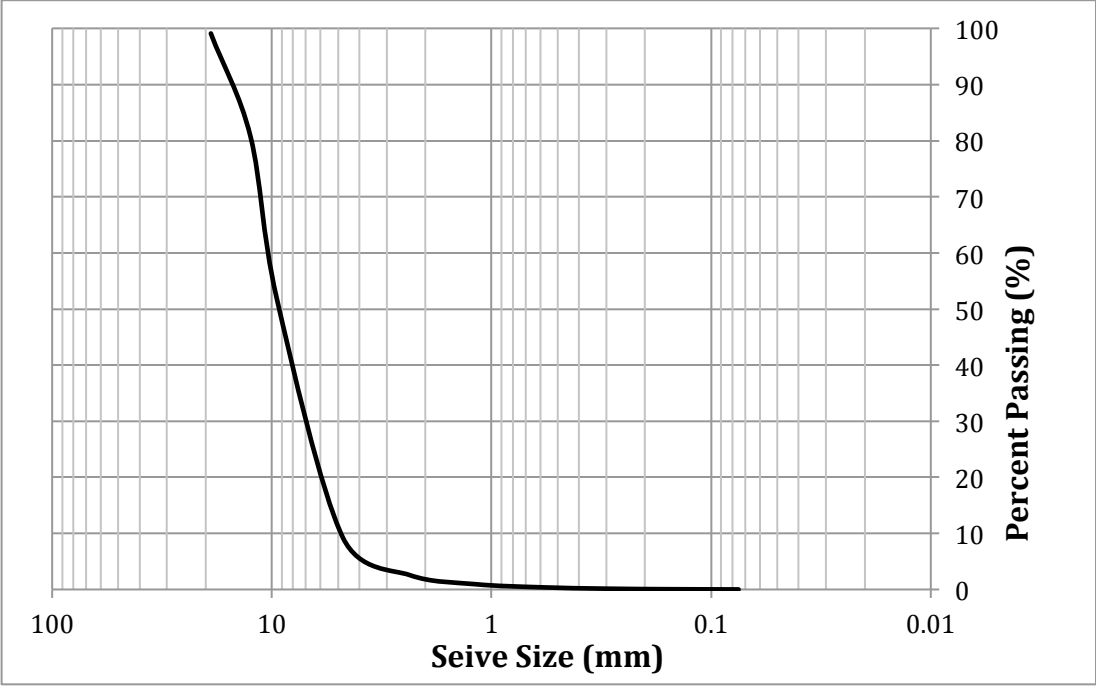
Figure 4.1 Sieve Analysis of Coconut Shells as per ASTM C136
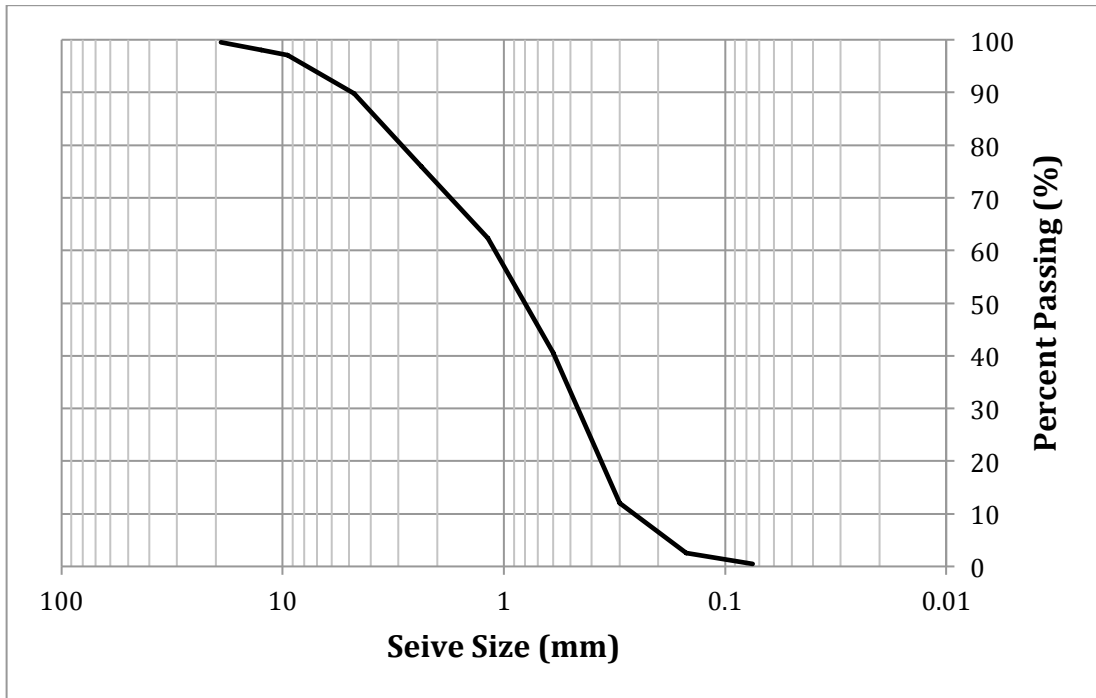
Figure 4.2 Sieve Analysis of Fine Aggregate as per ASTM C136

Each type of coarse waste aggregate, as well as the fine aggregate, was analyzed according to ASTM Standards for its bulk density (ASTM C29) and specific gravity (ASTM C127) (ASTM 1998). The results of these analyses are summarized in Table 4.1.

Table 4.1 Bulk Density and Specific Gravity of Aggregates Used at Saturated Surface Dry (SSD) Condition

	Bulk Density	Specific Gravity
Fine Aggregate	104.3 lb/ft^3 (1,670.7 kg/m^3)	1.67
Crushed Coconut Shell	39.2 lb/ft^3 (627.9 kg/m^3)	1.46
Sisal Fiber Twine	21.2 lb/ft^3 (339.6 kg/m^3)	1.02
Shredded Water Bottle Plastic	3.8 lb/ft^3 (60.9 kg/m^3)	1.43

4.2 Mix Designs

Design of the concrete mixes requires selection of the relative amounts of water, cement, and coarse and fine aggregate. First, the weight of water added was determined. Concrete mixes for CMUs typically have no or low slump in order to allow for immediate de-molding. Therefore, the lowest slump listed in ACI 211.2-98 was used for determining mix proportions (American Concrete Institute 2004). As summarized in Table 4.2, based on a slump of 1 to 2 in. and a nominal aggregate size of 3/4 inch for coconut shells and 3/8 inch for PET plastic and sisal fiber, water additions of 315 lb/yd^3 (5,045.8 kg/m^3) and 350 lb/yd^3 (5,606.5 kg/m^3) were selected for the respective test mixtures.

Table 4.2 Approximate Water and Air Content Requirements for Different Slumps and Nominal Maximum Sizes of Aggregate

Aggregate Size	3/8 in. (9.5 mm)	½ in. (12.7 mm)	¾ in (19.0 mm)
Non air-entrained concrete			
	Water, lb/yd^3 (kg/m^3) of concrete		
Slump, 1 to 2 in. (25 to 50 mm)	350 (208)	335 (199)	315 (187)
Slump, 3 to 4 in. (75 to 100 mm)	385 (228)	365 (217)	340 (202)
Slump, 5 to 6 in. (125 to 150 mm)	400 (237)	375 (222)	350 (208)
	Approximate amount of entrapped air in non air-entrained concrete, %		
	3	2.5	2

*Adapted from Table 3.2 from ACI 211.2-98 (American Concrete Institute 2004).

Once the water content was determined, the cement addition was calculated based on the desired strength and corresponding water to cement (w/c) ratio. ASTM C90 requires that load bearing CMUs have an average compressive strength of 1900 psi (13.1 MPa) for three blocks and at least 1700 psi (11.7 MPa) for each block after 28 days of curing (ASTM 2012). In addition, ACI 211.2-98 suggests that the average strength selected for design exceeds the specified strength by a "sufficient margin" (American Concrete Institute 2004). Based on these guidelines, strengths of 5000

psi (34.5 MPa) and 3000 psi (20.7 MPa) were chosen for the design strengths in this

study as being sufficiently greater than the minimum three-block average strength.

As summarized in Table 4.3, according to ACI 211.2-98, these strengths can be

achieved in non air-entrained concrete by w/c ratios of 0.48 and 0.68, respectively,

(American Concrete Institute 2004) after 28 days of curing.

Table 4.3 Relationships Between w/c and Compressive Strength of Concrete

Compressive Strength at 28 days, psi (MPa)	Approximate water-cement (w/c) ratio, by weight	
	Nonair-entrained concrete	Air-entrained concrete
6000 (41.4)	0.41	--
5000 (34.5)	0.48	0.40
4000 (27.6)	0.57	0.48
3000 (20.7)	0.68	0.59
2000 (13.8)	0.82	0.74

*Adapted from Table 3.3 from ACI 211.2-98 (American Concrete Institute

2004)

Once the w/c ratio was chosen, the amount of cement that should be added to each

mix was determined by back calculating from the estimated water content and

dividing by the w/c ratio, as summarized in Table 4.4. Thus, for a strength of 3000

psi (20.7 MPa), the cement content was calculated to be 463.24 lb/yd^3 (7,420.4

kg/m^3) for coconut shells and 514.71 lb/yd^3 (8,244.9 kg/m^3) for both PET plastic and

sisal fiber. For a strength of 5000 psi (34.5 MPa), 656.25 lb/yd^3 (10,512.1 kg/m^3)

and 729.17 lb/yd^3 (11,680.2 kg/m^3) were calculated for coconut shells and PET/sisal

fiber, respectively. This combination of three coarse aggregates and two design

strengths defines the six test mixes used in this study, as summarized in Table 4.4.

Table 4.4 Calculation for Cement Content for Test Mixtures 1-6

Mix	Coarse Aggregate	Estimated Projected Strength	Estimated Water Content	w/c	Calculation	Cement Content
Mix 1 (M1)	Coconut Shells	3000 psi (20.7 MPa)	315 lb/yd^3 (5,045.8 kg/m^3)	0.68	315/0.68 (5,045.8/0.68)	463.24 lb/yd^3 (7,420.4 kg/m^3)
Mix 2 (M2)	Coconut Shells	5000 psi (34.5 MPa)	315 lb/yd^3 (5,045.8 kg/m^3)	0.48	315/0.48 (5,045.8/0.48)	656.25 lb/yd^3 (10,512.1 kg/m^3)
Mix 3 (M3)	Sisal Fiber	3000 psi (20.7 MPa)	350 lb/yd^3 (5,606.5 kg/m^3)	0.68	350/0.68 (5,606.5/0.68)	514.71 lb/yd^3 (8,244.9 kg/m^3)
Mix 4 (M4)	Sisal Fiber	5000 psi (34.5 MPa)	350 lb/yd^3 (5,606.5 kg/m^3)	0.48	350/0.48 (5,606.5/0.48)	729.17 lb/yd^3 (11,680.2 kg/m^3)
Mix 5 (M5)	PET Plastic	3000 psi (20.7 MPa)	350 lb/yd^3 (5,606.5 kg/m^3)	0.68	350/0.68 (5,606.5/0.68)	514.71 lb/yd^3 (8,244.9 kg/m^3)
Mix 6 (M6)	PET Plastic	5000 psi (34.5 MPa)	350 lb/yd^3 (5,606.5 kg/m^3)	0.48	350/0.48 (5,606.5/0.48)	729.17 lb/yd^3 (11,680.2 kg/m^3)

Finally, the required volume of coarse aggregate per unit volume of concrete was determined from ACI 211.2-98 (American Concrete Institute 2004) by using the fineness modulus of the fine aggregate and the nominal maximum size of the coarse lightweight aggregate. In particular, Table 3.5 from ACI 211.2-98, which is re-created here in Table 4.5, defines the volume of oven-dry loose coarse aggregates per unit volume of concrete based on the maximum size aggregate used in the design mix, and the fineness modulus of the fine aggregate. The fineness modulus of the sand used in this study was 3.22. Because the highest fineness modulus listed in the Table was 3.00, and volume ratios in the table decreased linearly with the fineness modulus, extrapolation was used to determine the appropriate volume ratios to use for a fineness modulus of 3.22. Thus, for aggregate with a nominal maximum size of 3/8 inch (9.5 mm) (PET and sisal fiber), a volume ratio of 0.48 was estimated through extrapolation, while 0.64 was estimated as the volume ratio for aggregate with a nominal maximum size of 3/4 inch (19.1 mm) (coconut shells). These volume ratios were used but the extrapolation performed was incorrect. The appropriate volume ratios are 0.498 and 0.658. For each waste aggregate, the estimated aggregate volume/concrete volume ratio was multiplied by the respective bulk density for the aggregate to obtain the mass of each course aggregate to add per yd^3 of concrete. These bulk densities of the coarse aggregates are reported above in Table 4.1. The result was then multiplied by 0.75 to accommodate the desired batch size. In error, the resulting weights for sisal fiber and PET plastic were not

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multiplied by this 0.75 factor. For coconut shells, the coarse aggregate addition was

677.4 lb (307.4 kg) aggregate for 1 yd^3 (0.02 m^3) of concrete and 18.82 lb for 3/4 ft^3

of concrete. For sisal fiber and PET plastic, the coarse aggregate addition used was

49.1 lb (22.3 kg) and 274.9 lb (124.7 kg), respectively, per 3/4 ft^3 (0.02 m^3). These

waste products served as a 100% replacement of gravel as a coarse aggregate.

Table 4.5 Volume of Coarse Aggregate per Unit of Volume of Concrete

Maximum size of aggregate, in. (mm)	Volume of oven-dry loose coarse aggregates per unit volume of concrete for different fineness moduli of sand			
	2.40	2.60	2.80	3.00
3/8 (9.5)	0.58	0.56	0.54	0.52
1/2 (12.7)	0.67	0.65	0.63	0.61
3/4 (19.0)	0.74	0.72	0.70	0.68

*Adapted from Table 3.5 from ACI 211.2-98 (American Concrete Institute

2004)

Finally, based on the previously determined proportions and material densities, for

each mix design the necessary amount of fine aggregate was estimated to fill the

balance of needed material. To do this, an estimate of the lightweight concrete

weight was determined based on each lightweight aggregate's specific gravity and

the predicted air content from Table 4.6 (American Concrete Institute 2004). This

table is for air-entrained concrete but was used for reference due to the fact that

estimates for non-air-entrained concrete were not available. For each test mix, the

estimate associated with the respective specific gravity and 4% air content was used

as a starting point in calculating the mass of fine aggregate.

Table 4.6 First Estimate of Weight of Fresh Lightweight Concrete

Specific Gravity Factor	First estimate of lightweight concrete weight, lb/yd^3 (kg/m^3)		
	Air-entrained concrete		
	4%	6%	8%
1.00	2690 (1596)	2630 (1561)	2560 (1519)
1.20	2830 (1680)	2770 (1644)	2710 (1608)
1.40	2980 (1769)	2910 (1727)	2850 (1691)
1.60	3120 (1852)	3050 (1810)	2990 (1775)
1.80	3260 (1935)	3200 (1899)	3130 (1858)
2.00	3410 (2024)	3340 (1982)	3270 (1941)

 * Adapted from Table 3.6 from ACI 211.2-98 (American Concrete Institute 2004)

The lightweight concrete weights obtained from Table 4.6 were next refined based

on adjustments allowed in ACI 211.2-98 (American Concrete Institute 2004).

According to ACI 211.2-98, Table 4.6 consists of values based on concrete mixes of

550 lb/yd^3 of cement and water requirements based on 3 to 4 inch slump values (340

lb of water). These values can be adjusted based on differences in water and cement

values. For every 10 lb difference in mixing water, the weight from Table 4.6 was

adjusted 15 lb in the opposite direction, and for every 100 lb difference in cement,

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the weight was adjusted 15 lb in the same direction. For example, because the coconut mixes called for less than 340 lb of water, the estimated weight was increased and because the mix called for less than 550 lb of cement, the estimated weight was decreased. Table 4.7 shows the calculations for Mix 1 from Table 4.4, using coconut shells (specific gravity = 1.46) and an estimated strength of 3000 psi, with mixing water at 315 lb/yd^3 and cement at 463.24 lb/yd^3. From Table 4.6, with 4% air entrained concrete and specific gravity = 1.4, the first estimate of the concrete weight is 2980 lb/yd^3, and with the adjustments determined in Table 4.7 for Mix 1, the adjusted concrete weight = 3,004.5 lb/yd^3.

Table 4.7 Sample Calculation for Adjusted Initial Weight Estimate of Fresh Concrete using Mix 1

	Material Difference	Adjustment Factors	Adjustment Amount	Original Estimate: = 2980 lb/yd^3 (1,768.0 kg/m^3)
Water	$315 - 340 = -25$	$\div10\times15$	37.5	+37.5
Cement	$463.24 - 550 = -86.76$	$\div100\times15$	13.014	-13.0
				3,004.5 lb/yd^3 (1,782.5 kg/m^3)

Next, the proportions selected for water, cement, and coarse aggregate were subtracted from the estimated weight to find the approximate weight of fine aggregate required. These calculations are summarized in Table 4.8 for Mix 1. For that mix, the value of fine aggregate required was calculated to be 1,548.9 lb/yd^3 (918.9 kg/m^3). As illustrated in Table 4.8, the mix values that had all been calculated as the pounds (kilograms) required for 1 yd^3 (0.76 m^3) of concrete, were then adjusted to the pounds (kilograms) of material required per 3/4 ft^3 (0.02 m^3) batch of

concrete as used in the laboratory, due to the size of the mixer. Following the same

approach as for Mix 1, the same calculations were performed for Mixes 2 – 6, and

the resulting mix designs for all six mixes are presented in Table 4.9.

Table 4.8 Sample Calculation for Finding Necessary Amount of Fine Aggregate

	Est. Weight	Water	Cement	Coarse Agg.	Calculation	Fine Agg.
lb/yd^3	3,004.5	315	463.24	677.4	3,004.5 −315.0−463.2−677.4	1,548.9
Divide by 27 and multiply by 0.75 in order to produce ¾ ft^3 of concrete						
lb/ft^3	83.46	8.75	12.87	18.82		43.0

Table 4.9 Test Mix Designs by Weight for 3/4 ft^3 of Mixes 1 to 6

	Water	Cement	Coarse Aggregate	Fine Aggregate
M1	8.75 lb (4.0 kg)	12.87 lb (5.8 kg)	18.82 lb (8.5 kg)	43.02 lb (19.5 kg)
M2	8.75 lb (4.0 kg)	18.23 lb (8.3 kg)	18.82 lb (8.5 kg)	37.66 lb (17.1 kg)
M3	9.72 lb (4.4 kg)	14.30 lb (6.5 kg)	10.18 lb (4.6 kg)	39.96 lb (18.1 kg)
M4	9.72 lb (4.4 kg)	20.25 lb (9.2 kg)	10.18 lb (4.6 kg)	34.00 lb (15.4 kg)
M5	9.72 lb (4.4 kg)	14.30 lb (6.5 kg)	1.82 lb (0.8 kg)	56.37 lb (25.6 kg)
M6	9.72 lb (4.4 kg)	20.25 lb (9.2 kg)	1.82 lb (0.8 kg)	50.42 lb (22.9 kg)

4.3 Testing Concrete Properties

Due to the inability to test masonry units, cylinder test specimens were used for testing the concrete properties. Specifically, six samples were prepared for each mix design in 4 by 8 inch (10.2 by 20.3 cm) cylindrical molds, and tested at the fresh and hardened states. The procedure for mixing the lightweight concrete used in this study was based on the procedure outlined in "Producing Structural Lightweight Concrete Block" (Schierhorn 1996b) and is as follows:

1. Charge the mixer with all lightweight aggregate
2. Add ½ to 2/3 of the total mixing water
3. Mix for 30 seconds
4. Add all cementitious material
5. Add the balance of the required mixing water
6. Continue mixing an absolute minimum of two to four minutes
7. If additional water is required to bring the mix to the right consistency, mix for an additional one minute
8. Immediately pour mixture into mold

Note that because lightweight aggregate is generally more porous and absorptive than normal weight aggregate, it can have more of an effect on the water/cement ratio, and its state before mixing can have significant effects (ACI 2009). Due to these absorption qualities, mixing in the oven-dry state can lead to a need for an

increased proportion of water in the mix. It is typically assumed that lightweight

aggregate is in one of four stages: oven-dry, air-dry, saturated surface-dry, or wet

(ACI 2009). To decrease the variability in absorption of water by the aggregates for

this study, the lightweight aggregates were used in the test mixes in the 'saturated

surface-dry' (SSD) condition. The water absorbed by the coarse aggregate is in

addition to the mix design water amount. This was due to the difficulty of

calculating the absorption capabilities of each coarse aggregate. To achieve this

state, prior to following the mix procedure outlined above, the aggregate was soaked

for 24 hours and then dried with an absorbent towel. Mixing lightweight aggregate in

this state not only decreases the variability in water absorption by the aggregates, but

it also has the additional benefit of decreased segregation (ACI 2009). In addition to

mixing in SSD, the aggregate was also mixed with 1/2 to 2/3 of the required mixing

water for thirty seconds prior to combining it with the remaining materials, as per the

instructions above. Although the water/cement ratio does not directly impact the

compressive strength of lightweight concrete greatly, the impact of the lightweight

aggregate on the water/cement ratio is still extremely important. For example, a ratio

that is too high will cause the cement paste to slide off the aggregate, and a ratio that

is too low will prevent adequate cohesion (Short and Kinniburgh 1976). The

water/cement ratio is dependent on the type of aggregate being used and can only be

discovered through trial mixes. For this study, the initial mixtures were estimated

with the use of ACI 211.2-98 (ACI 2009), as described above.

Immediately following mixing, the concrete was tested in the fresh state. Specifically, the slump (ASTM C143), temperature (ASTM C1064), unit weight (ASTM C138), and air content (ASTM C138) for each batch were determined (ASTM 1998).

The remaining concrete for each mix was cast into six 4" (10.2 cm) molds in two lifts, with 25 rods per lift. Using a trowel, molds were then leveled and set to cure for 7 days at approximately 65° Fahrenheit (18.3° Celsius) before removing the specimens from their molds. With the PET plastic mixtures, leveling the top of the molds was difficult due to the length of the waste aggregate. To remedy this, when specimens were demolded, any plastic protruding from the top was cut at the base. After 28 days of curing, three specimens for each mix were tested in a hardened state for dry density (ASTM C567), water absorption (ASTM C140) (ASTM 2013), and compressive strength (ASTM C39) (ASTM 1998).

Water absorption and dry density were tested in general accordance with ASTM C140 after 28 days (ASTM 2013). The 28-day specimens were weighed and then immersed in water for 24 hours as per ASTM C140 with no less than 6 inches (15.2 cm) of water above the specimen and greater than 1/8 inches (0.3 cm) between the bottom of the specimen and the tank (ASTM 2013). The specimen was weighed when completely immersed in water for its immersed weight and then removed from the water and allowed to drain for 60 ± 5s before removing visible surface water with

a damp cloth. The specimen was then weighed again for the saturated weight. The weight taken prior to soaking was used as the dry weight in the calculations for absorption and dry density. Calculations for water absorption and dry density were done using the equations provided by ASTM C140 (ASTM 2012).

Compressive strength was tested in accordance with ASTM C39 at a rate of 440 pounds per second (199.6 kg per second) beginning with a load of 750 pounds (340.2 kg) using an International ADR-auto compression machine (ASTM 1998). Three specimens for each mix were tested after 28 days of curing.

Figure 4.3 International ADR-Auto Compression Machine

5.0 Results and Discussion

5.1 Measurements with Fresh Concrete

Immediately following mixing, the concrete was tested in the fresh state for four

properties: the slump, temperature, unit weight, and air content. The results of these

tests for each mix are summarized in Table 5.1. As discussed in Chapter 4, in

choosing the component proportions for each mix, the slump goal was between 1 and

2 inches (2.54 and 5.08 cm). However, for the coconut shell mixes and the sisal

fiber mixes, the slump measurements were significantly higher than the goal, ranging

from 4.0 inches (10.2 cm) to 9.5 inches (24.1 cm). The nature of the coconut shell

aggregate may explain the high slump in Mix 1 and 2. According to Gunasekaran et

al. (2012), coconut shell aggregate increases the workability of concrete due to its

one smooth surface. Also, when estimating proportions, a nominal maximum of 3/4

inch (1.9 cm) was used to choose values from ACI 211.2-98. This turned out to

have been a poor representation of the aggregate, because the thickness of the

coconut shell aggregate, although varied, never exceeded 3/16 inch (4.8 mm). This

over-estimation of the size of the aggregate may have led to the selection of

proportions that resulted in unexpectedly high slumps.

Because no air entrainment admixtures were used, the air content was expected to be

around 3 percent (ACI 2004), and the values for the coconut shell (M1 and M2) and

PET (M5 and M6) aggregates were consistent with this expectation. However, the

mixes using sisal fiber as the waste aggregate had an air content much higher than that, with values of 20.0 % (Figure 5.1) and 11.4 % (Figure 5.2) for Mixes 3 and 4, respectively. The high air content in Mix 3 and 4 may have aided in the increased slump observed in these mixes, as air in concrete can lead to increased workability (NRCS 1976). In addition to an extremely high air content, Mix 3 also had a low unit weight compared to the expected values (e.g., Table 4.6). Mix 4, on the other hand, shows a more appropriate unit weight, and while the air content is lower than in Mix 3, it is still significantly higher than the expected 3 percent.

Table 5.1 Temperature, Unit Weight, Air Content, and Slump

Mix	Coarse aggregate/ Initial estimated strength	Temperature	Unit Weight	Air Content	Slump
M1	Coconut shell 3000 psi (20.7 MPa)	65.8 ° F (18.8 °C)	108.9 lb/ft^3 (1,744.4 kg/m^3)	1.7%	9.5 in (24.1 cm)
M2	Coconut shell 5000 psi (34.5 MPa)	65.6 ° F (18.7 °C)	114.0 lb/ft^3 (1,826.1 kg/m^3)	5.1%	7.8 in (19.8 cm)
M3	Sisal fiber 3000 psi (20.7 MPa)	64.4 ° F (18 °C)	95.2 lb/ft^3 (1,525.0 kg/m^3)	20.0%	4.0 in (10.2 cm)
M4	Sisal fiber 5000 psi (34.5 MPa)	67.2 ° F (19.6 °C)	108.9 lb/ft^3 (1,744.4 kg/m^3)	11.4%	7.3 in (18.5 cm)
M5	PET 3000 psi (20.7 MPa)	60.5 ° F (15.8 °C)	141.8 lb/ft^3 (2,271.4 kg/m^3)	3%	1.8 in (4.6 cm)
M6	PET 5000 psi (34.5 MPa)	60.6 ° F (15.9 °C)	142.8 lb/ft^3 (2,287.4 kg/m^3)	3%	1.9 in (4.8 cm)

Figure 5.1 Air-Entrainment Reading for Mix 3

Figure 5.2 Air-Entrainment Reading for Mix 4

5.2 Measurements with Cured Concrete

After 28 days of curing, three specimens for each mix were tested in a hardened state

for compressive strength (Table 5.2), dry density (Table 5.3), and water absorption

(Table 5.4). For each test, the corresponding tables summarize the results for the

compressive strength of the three cylinders for each mix, along with the average

value for the triplicate cylinders. Importantly, for concrete to be classified as

lightweight concrete used for load-bearing masonry units, an average compressive

strength of 1900 psi (13.1 MPa) for three units is required, with a compressive

strength of no less than 1700 psi (11.7 MPa) for any individual unit (ASTM 2012).

In addition, the average dry density of three units must be below 105 lb/ft^3 (1,681.9

kg/m^3), and the average water absorption must be less than 18 lb/ft^3 (288.3 kg/m^3) (<

20 lb/ft^3 (320.4 kg/m^3) for an individual unit). The results for each mix were

compared to these standards.

Table 5.2 Measured Compressive Strength After 28 Days

Compressive Strength	Coarse aggregate/ Initial estimated strength	Cylinder 1	Cylinder 2	Cylinder 3	Average
M1	Coconut shell 3000 psi	525.2 psi (3.6 MPa)	701.1 psi (4.8 MPa)	729.7 psi (5.0 MPa)	652.0 psi (4.5 MPa)
M2	Coconut shell 5000 psi	1947.3 psi (13.4 MPa)	1830.3 psi (12.6 MPa)	2100.8 psi (14.5 MPa)	1959.5 psi (13.5 MPa)
M3	Sisal fiber 3000 psi	417.0 psi	447.2 psi	418.6 psi	427.6 psi

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		(2.9 MPa)	(3.1 MPa)	(2.9 MPa)	(2.9 MPa)
M4	Sisal fiber 5000 psi	1515.2 psi (10.4 MPa)	1395.8 psi (9.6 MPa)	1500.0 psi (10.3 MPa)	1470.3 psi (10.1 MPa)
M5	PET 3000 psi	3079.6 psi (21.2 MPa)	2546.5 psi (17.6 MPa)	2816.2 psi (19.4 MPa)	2814.1 psi (19.4 MPa)
M6	PET 5000 psi	2407.2 psi (16.6 MPa)	3051.8 psi (21.0 MPa)	2789.2 psi (19.2 MPa)	2749.4 psi (19.0 MPa)

Table 5.3 Measured Dry Density after 28 days

Dry Density	Coarse aggregate/ Initial estimated strength	Cylinder 1	Cylinder 2	Cylinder 3	Average
M1	Coconut shell 3000 psi	102.2 lb/ft^3 (1,637.1 kg/m^3)	98.2 lb/ft^3 (1,573.0 kg/m^3)	109.8 lb/ft^3 (1,758.8 kg/m^3)	103.4 lb/ft^3 (1,656.3 kg/m^3)
M2	Coconut shell 5000 psi	98.6 lb/ft^3 (1,579.4 kg/m^3)	99.1 lb/ft^3 (1,587.4 kg/m^3)	98.3 lb/ft^3 (1,574.6 kg/m^3)	98.7 lb/ft^3 (1,581.0 kg/m^3)
M3	Sisal fiber 3000 psi	77.9 lb/ft^3 (1,247.8 kg/m^3)	80.9 lb/ft^3 (1,295.9 kg/m^3)	80.4 lb/ft^3 (1,287.9 kg/m^3)	79.7 lb/ft^3 (1,276.7 kg/m^3)
M4	Sisal fiber 5000 psi	94.3 lb/ft^3 (1,510.5 kg/m^3)	93.2 lb/ft^3 (1,492.9 kg/m^3)	93.7 lb/ft^3 (1,500.9 kg/m^3)	93.7 lb/ft^3 (1,500.9 kg/m^3)
M5	PET 3000 psi	128.0 lb/ft^3 (2,050.4 kg/m^3)	127.2 lb/ft^3 (2,037.5 kg/m^3)	127.3 lb/ft^3 (2,039.2 kg/m^3)	127.5 lb/ft^3 (2,042.4 kg/m^3)
M6	PET 5000 psi	122.9 lb/ft^3 (1,968.7 kg/m^3)	124.5 lb/ft^3 (1,994.3 kg/m^3)	123.7 lb/ft^3 (1,981.5 kg/m^3)	123.7 lb/ft^3 (1,981.5 kg/m^3)

Table 5.4 Measured Water Absorption after 28 days

Water Absorption	Coarse aggregate/ Initial estimated strength	Cylinder 1	Cylinder 2	Cylinder 3	Average
M1	Coconut shell 3000 psi	16.8 lb/ft^3 (269.1 kg/m^3)	18.1 lb/ft^3 (289.9 kg/m^3)	15.7 lb/ft^3 (251.5 kg/m^3)	16.9 lb/ft^3 (270.7 kg/m^3)
M2	Coconut shell 5000 psi	15.6 lb/ft^3 (249.9 kg/m^3)	15.3 lb/ft^3 (245.1 kg/m^3)	15.5 lb/ft^3 (248.3 kg/m^3)	15.5 lb/ft^3 (248.3 kg/m^3)
M3	Sisal fiber 3000 psi	17.6 lb/ft^3 (281.9 kg/m^3)	16.5 lb/ft^3 (264.3 kg/m^3)	16.6 lb/ft^3 (265.9 kg/m^3)	16.9 lb/ft^3 (270.7 kg/m^3)
M4	Sisal fiber 5000 psi	19.0 lb/ft^3 (304.4 kg/m^3)	19.2 lb/ft^3 (307.6 kg/m^3)	18.8 lb/ft^3 (301.1 kg/m^3)	19.0 lb/ft^3 (304.4 kg/m^3)
M5	PET 3000 psi	13.5 lb/ft^3 (216.2 kg/m^3)	13.9 lb/ft^3 (222.7 kg/m^3)	13.7 lb/ft^3 (219.5 kg/m^3)	13.7 lb/ft^3 (219.5 kg/m^3)
M6	PET 5000 psi	15.3 lb/ft^3 (245.1 kg/m^3)	14.9 lb/ft^3 (238.7 kg/m^3)	15.3 lb/ft^3 (245.1 kg/m^3)	15.1 lb/ft^3 (241.9 kg/m^3)

Mix 1, using coconut shell as waste aggregate, failed to meet the compressive

strength requirements set forth by ASTM (2012) achieving an average strength of

only 652 psi (4.5 MPa), but succeeded in meeting the other two requirements with a

weight of 103.4 lb/ft^3 (1656.3 kg/m^3) and an absorption of 16.9 lb/ft^3 (270.7 kg/m^3).

The high slump of this mix likely indicates excess water, which may also have

affected the strength. Mix 2 experienced a lower slump, and succeeded in meeting

the requirements for compressive strength, density, and absorption. Reducing the

water content in the mix will likely lead to lower slump results, and higher strengths

in concrete (ACI 2004). Another flaw that was observed in both coconut shell mixes

was a lack of bonding between the concrete and the aggregate, as demonstrated by

how easily the coconut shell fragments were pulled from the specimens. This may

be due to compatibility issues between the concrete paste and the coconut shell

aggregate, or it may be another result of an excess of water in the mix. A coconut

shell cylinder (M1) immediately after failure is shown in Figure 5.3.

The strengths observed in this study using the coconut shell mixtures (M1 and M2)

are consistent with the lower end of a range of strengths observed in a study

performed by Gunasekaran et al. (2011) on the mechanical and bond properties of

coconut shell concrete. After an optimization of material ratios (cement, water,

coconut shell, and sand), their study showed that compressive strength increased

with a decrease in slump (Gunasekaran et al. 2011), which is also consistent with the

current study. In another study performed by Olanipekun at al. (2006), adequate

strengths for meeting ASTM standards were also observed with mixes using coconut shell as a coarse aggregate replacement. However, varying slumps were not presented and, therefore, cannot be compared to the results in this study. Taken together, the results of this study, coupled with those from the literature, indicate that coconut shell aggregate, when used with the correct material ratios, has the potential to produce lightweight concrete that meets the requirements for compressive strength, dry density, and water absorption.

Figure 5.3 Coconut Shell Cylinder (M1) Immediately After Failure

The test cylinders for Mix 3 and 4 with sisal fiber were below the maximum allowed dry density and Mix 3 was below the maximum allowed water absorption (Tables 5.3 and 5.4). However, both failed early under compression, and only reached an

average compressive strength of 427.7 psi (2.9 MPa) and 1470.3 psi (10.1 MPa), respectively. These values are much lower than the required 1900.0 psi (13.1 MPa) and, therefore, these mixes failed to meet all of the requirements specified in ASTM C90 for lightweight concrete (ASTM 2012). Interestingly, unlike the rest of the test cylinders, these cylinders stayed almost completely intact during failure, and the failure was less visible, as illustrated by Figure 5.4, which shows a sisal fiber cylinder immediately after failure. One cylinder was compressed beyond failure, as shown in Figure 5.5, to better illustrate the failure locations. Based on these and other visual assessments, when the Mix 3 specimens failed, they failed in shear but throughout the entirety of the specimens. Mix 4 specimens, however, failed in shear but only near the top quarter of the specimens.

Figure 5.4 Sisal Fiber Cylinder (M3) Immediately After Failure

Figure 5.5 Sisal Fiber Cylinder 1 (M3) Compressed Beyond Failure

These results are consistent with other research that has been done on sisal fiber as concrete reinforcement. In a review, Toledo Filho et al. (1999) report that sisal fiber can provide a way for stresses to be re-distributed and for cracks to be bridged through improved pullout processes. Although the current study did not look at tensile strengths, these benefits have been found to improve concrete's abilities under tensile stress ((Toledo Filho et al.1999), and references therein). Compressive strength in one study has been found to decrease with an increased percentage of sisal fiber included in concrete mixes (Toledo Filho 1999), which is consistent with the results of this study. Together, these results indicate that sisal fiber is not an adequate coarse aggregate on its own, and other aggregate materials would need to be incorporated to reap the benefits of sisal fibers, without losing the functionality of the concrete.

Another interesting result obtained with Mixes 3 and 4 is the air content that resulted from using sisal fiber as a waste aggregate (Table 5.1). This is important because inducing air in concrete allows for better workability of concrete. It also leads to a reduction in water requirements without a loss in strength. This decreased water requirement can lead to less drying shrinkage, and less pressure on communities in places like Kilwa to provide a typically scarce commodity. In addition to the decreased need for water, according to the Natural Resource Conservation Center, air entrainment can often lead to a better resistance to scaling in hardened concrete (NRCS 1976), a result that was observed during this study's compressive strength

testing. When testing for compressive strength in the coconut shell and the PET plastic specimens, concrete crumbled from the molded shape after failure had been initiated, whereas almost none pulled away from the specimens using sisal fiber throughout the testing process and afterwards.

Test units using Mix 5 and 6 and PET plastic as waste aggregate easily met ASTM's compressive strength requirements, with average compressive strengths for Mix 5 and 6 of 2814.1 psi (19.4 MPa) and 2749.4 psi (19.0 MPa), respectively. The lowest compressive strength for a single unit of each mix was 2546.5 psi (17.6 MPa) for Mix 5 and 2407.2 psi (16.6 MPa) for Mix 6. Curiously, Mix 5, which had material proportions for a compressive strength of 3000 psi (20.7 MPa), produced a higher average strength than Mix 6, which was proportioned for 5000 psi (34.5 MPa). A PET cylinder (M5) immediately after failure is shown in Figure 5.6.

Mixes 5 and 6 also met the ASTM (2012) requirements for water absorption, but the oven dry density for both mixtures was too high to be considered lightweight concrete, with averages of 127.5 lb/ft^3 (2,042.4 kg/m^3) and 123.7 lb/ft^3 (1,981.5 kg/m^3) for Mix 5 and 6, respectively. Although this prevents these two mixes from being considered 'lightweight,' Mix 6 does fall within the dry density range specified for medium weight concrete (> 105 lb/ft^3 (1,681.9 kg/m^3) and < 125 lb/ft^3 (2,002.3 kg/m^3)), and Mix 5 is very close to this classification (ASTM 2012). According to ASTM C140, the water absorption values, however, were slightly high

for these specimens to be considered medium weight concrete (ASTM 2012).

Nevertheless, with some adjustments to proportions it may be possible to meet the

medium weight concrete standards. Medium weight concrete would not have the

same level of benefit as lightweight concrete, but it would still be an improvement

when compared to normal weight concrete in terms of the materials required and

labor effort, and less strength would be sacrificed.

Figure 5.6 PET Plastic Cylinder (M5) Immediately After Failure

In a study performed by Choi et al. (2004) on PET plastic in concrete, compressive

strengths were found to be higher than the ones observed in this study. In addition to

the higher compressive strengths, the dry densities observed were lower than the

ones observed in this study, although they still were not adequate to be considered

lightweight by ASTM (2012) Standards. One important difference between the

study by Choi et al. (2004) and the current study is that Choi et al. (2004) also added granulated blast furnace slag and crushed stone aggregate in their concrete mix. The additions of these two materials to the mix probably decreased densities and increased compressive strengths, indicating that the addition of the granulated blast furnace slag could help with the dry density reduction needed to conform to ASTM standards. Although it is likely that the additional coarse aggregate aided in increasing the compressive strengths in Choi et al.'s (2004) experiment, the appropriate strengths were attained in this study without such additions, indicating that the coarse aggregate addition is unnecessary for that purpose.

6.0 Summary and Conclusions

Three solid waste materials commonly found in Tanzania—coconut shells, PET plastic, and sisal fibers—were tested for their potential to be beneficially reused as lightweight coarse aggregate in lightweight concrete. Two concrete mixes were devised for each material—one with an initial estimated strength of 3000 psi (20.7 MPa), the other 5000 psi (34.5 MPa)—for a total of six mixes. Immediately following mixing, the fresh concrete mixes were tested for their slump, temperature, unit weight, and air content. Then, after 28 days of curing, three specimens for each mix were tested in a hardened state for dry density, water absorption, and compressive strength.

Of the six mixes, only Mix 2 using coconut shells as coarse aggregate at a 100% replacement level, with an initial estimated strength of 5000 psi (34.5 MPa), met all three of the classification requirements set forth in ASTM C90 for the dry density, water absorption, and compressive strength of lightweight concrete. The successful testing of Mix 2 with the initial estimate for materials proportions demonstrates that with some adjustments, especially to water content and/or slump, lightweight concrete using coconut shells as a lightweight coarse aggregate has real potential for use in developing countries like Tanzania. Use of coconut shells as a lightweight coarse aggregate addresses issues with cost and weight of CMUs in developing countries where coconut shells are a common source of agricultural waste.

Furthermore, based on observations in this study, it is anticipated that the addition of a material that will help to more effectively bind the concrete to the coconut shell will result in a lightweight concrete with even better characteristics.

The two mixes using sisal fiber as a lightweight coarse aggregate did not meet the ASTM requirements for the compressive strength of lightweight concrete. However, the dry density of the concrete made using these mixes indicate that the addition of another coarse aggregate could aid with the compressive strength without causing the concrete to exceed the ASTM limits for density and water absorption. The sisal also seems to have potential as a locally available, cost effective air-entraining admixture in places where industrial air-entraining admixtures would be either extremely expensive or unavailable. Development of this potential could lead to concrete that requires less water, is less susceptible to spalling and scaling, and is more resistant to weathering.

Use of PET plastic as a lightweight coarse aggregate at the tested proportions produced concrete with adequate compressive strength that did not exceed the ASTM water absorption limits. However, the concrete produced was too heavy to be classified as lightweight concrete, although it was at the low end of the range for normal weight concrete and at the top of the range for medium weight concrete. Another option that may be more attainable with PET plastic would be to adjust the - proportions of the mix materials with a goal of reaching strength, absorption, and

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density classification requirements for medium weight concrete. Such an approach would still be beneficial to places like Kilwa, as the result would still reduce the accumulation of solid waste, and the blocks would be lighter than blocks currently in use.

In conclusion, in one form or another, all of the tested materials show promise for improving the building methods and materials of Kilwa, Lindi, Tanzania. In particular, with the application of these materials, dead loads will decrease resulting in more cost effective designs with less reinforcement. In addition, less aggregate will need to be purchased and, simultaneously, the accumulation of solid waste on the ground will be decreased. As a result, with this approach, the more buildings that are built, the greater the reduction in the solid waste disposal problem. Finally, with the use of CMUs made from lightweight concrete, laborers will tire less quickly, resulting in fewer injuries to them and shorter construction timelines for building owners.

7.0 Recommendations for Future Work

It is recommended that any future work on the beneficial re-use of waste materials as lightweight coarse aggregate should continue with the same materials used in this study, as these are some of the most widely available materials in Tanzania, and would make the application of this method in Kilwa the most feasible. In addition, the results obtained during this project suggest that there are several research questions with respect to these materials that are worth pursuing further. In particular, it is recommended that fine-tuning the proportions for a concrete mix using waste coconut shells as an aggregate would be beneficial.

For example, the data obtained in this study suggest that using one or both of the other two materials from this study could potentially solve some of the problems observed with the coconut shell mixes. Notably, sisal fiber almost completely eliminated the spalling and scaling typically observed in concrete specimens. The fact that this was the most noticeable weakness of the coconut shell mixes makes the idea of testing the addition of sisal fiber to the coconut shell mixes intriguing. This would also address the lack of strength that the sisal fiber mixes exhibited. Thus, by combining the coconut shells and sisal fibers into one concrete mix, the strengths of one material could potentially make up for the weaknesses in the other.

Beyond the possibilities of mixing coconut shells and sisal fibers, the abilities of sisal fiber as an air-entraining admixture are also worth pursuing. The air contents

produced in this study using sisal fibers are higher than recommended, but with additional research, a mix with the proportions needed to produce a beneficial percentage could potentially lead to a decrease in the amount of necessary mixing water and segregation in plastic concrete. In hardened concrete, an improved sisal mix could reduce scaling and enhance durability to weather related distresses. The development of this technology for developing countries could allow access to a low cost air-entraining admixture and, along with it, the benefits provided by such an amendment.

Finally, in addition to efforts to work with different concrete mixes, it is recommended that the effect of different curing conditions also be explored. According a long term study on compressive and bond strength of coconut shell aggregate by Gunasekaran et al. (2012), different methods of curing can result in different strengths. The specimens in the current study were all air cured, which has been found to produce the lowest strengths (Gunasekaran et al. 2012). Finding the curing method that will produce the highest strength for these mixes and then adapting the method for use in Tanzania would also help with the application and feasibility of beneficially re-using common solid waste materials as lightweight coarse aggregate.

8.0 References

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