Material Solutions for Rapidly Deployable Housing

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Abstract: **Post-destruction scenarios and lack of essential facilities in the immediate aftermath of disasters poses a significant and urgent threat. Post-disaster situations frequently see large amounts of displaced populations, with a desperate need for adequate housing. The challenge in providing housing after disasters is in the significant amount of time needed to repair or rebuild the shelters that were damaged, and the access to the labor and materials needed to build new structures. Temporary shelters need to be adaptable to different climates and cultures. This study aims to examine mortar-less solutions involving readily available agricultural waste that can be used as a key material in temporary housing construction. This study investigates the properties of insulative and cementitious material consisting of various agricultural materials, and provides a comparison with respect to their structural and thermal characteristics. A manufacturing process for the purposes of post-disaster home construction is also suggested.**

Keywords: **temporary housing, thermal insulation, sustainability, agricultural waste.**

1. INTRODUCTION

Infrastructure construction is one of the largest industrial employers, accounting for 10% of the gross domestic product (GDP) and 51.2% of the Gross fixed Capital Formation of EU-15 (Ortiz, Castells and Sonnemann 2009). However, the construction industry is also responsible for disproportionately high energy consumption, solid waste generation, external and internal pollution, global greenhouse gas emissions, environmental damage, and resource depletion (Melchert, 2007; Zimmermann, Althaus, & Haas, 2005). Along with promoting reduced consumption of non-renewable resources and energy, sustainable construction also explores more efficient material utilization, longevity and second life of products. Efficient application of resources and energy and longer life of products yields less waste and a lesser impact on the environment. The sustainable building can achieve a much lower consumption of energy and resources with prudent use, renovation, recycling, reuse and to their eventual demolition. Another central goal of sustainability is to minimize damage to the natural environment, through the efficient use of materials and energy.

Due to the lack of adequate disposal sites and expensive treatment methods, waste control and management has become one of the great challenges of modern society. Instead of considerable attention towards recycling and reusing of construction and demolition (C&D) waste, a very small percentage of cementitious and insulative materials are recycled in practice. The difficulty of separation, and lack of demand hinders the process of recycling most of the C&D wastes, aside from wood products. This significant amount of debris and waste in most cases overwhelm the existing solid waste management capacity. Also, disasters like earthquakes, tsunamis, floods, and hurricanes not only causes the collapse residential but also commercial and administrative buildings, but the economy and transportation systems of the affected area treatment plants, landfill and solid waste treatment facilities are vulnerable to the destruction as well. In this scenario, construction and demolition debris of temporary shelter and temporary housing contribute an additional burden.

According to UNDRO 1982, temporary housing are one of the neglected issues of humanitarian efforts. Decisions of providing temporary housing are usually associated with few complications. Where disaster survivors generally build their own permanent housing, importing materials, and building temporary housing can be more expensive than permanent house. In developed countries, permanent housing is expensive and temporary housing are preferable options for rehabilitation period. In Latin America, a permanent residential house costs approx. 5.4 times of the average annual income, In Africa the ratio of the cost of a house and average annual income is 12.5 :1 (Barakat,2003). Hence, building permanent housing takes long enough time, for the survivors to stay in a temporary tent or shelter. Additionally, temporary housing might extend the time needed to provide permanent housing, as it consumes resources, manpower and funding, which could have been used in building permanent housing. Housing processes are often intended to plan and implement rapidly, isolated from the political, social, and economic environment for the sake of speed (Barakat,2003). According to Sena, et al (2010), using local resources can quicken the restart of supply chains. The incorporation of local labor and resources in reduce the costs and increases the participation by the recipients.

The challenge in providing housing after disasters is in the significant amount of time needed to repair or rebuild the shelters that were damaged, and the access to the labor and materials needed to build new structures. The goal of this work is to determine what readily-available materials could be used in temporary housing that provide both adequate structural and thermal characteristics.

2. A REVIEW OF EXISTING TECHNOLOGY

A survey by Terpajova et al (2013) of historic and contemporary buildings reveals common trends in technological practice, and suggests guidelines for designing for disassembly. These guidelines cover issues like, use of fasteners, shape, and structure of product. The DfD principle regarding the use of homogenous materials is addressed through the grinding process producing a consistent insulation mix that can be reground with new material during the recycling phase. This material was chosen because it is rich in lignin and cellulose, the main components of binder-less fiberboard. Each year, several million tons of agricultural waste are disposed around the world, by incineration, landfills, and land applications. Using waste products as aggregates saves resources and cut down the pollution as it reduces volume of cement needed, reduces the agricultural waste, cost of aggregates, and also provides reinforcement to the cement. Some agricultural waste also have superior thermal resistance, which can be energy saving. Incorporating agricultural or other noncontiguous wastes in construction industry is not a new concept. Increasing interest in environment friendly, low waste and light weight material has initiated the need to investigate alternate construction materials. Advanced composite materials are replacing traditional building materials. Fiber reinforced polymers (FRP) and Fiber reinforced concrete are two of this group of new composite material, with profitable properties (Terpajova et al., 2013). Brick, masonry blocks, and Insulation blocks are one of the important material in construction industry. As the growing market demand for construction material has created a supply-demand gap, studies are being conducted on new and innovative design to develop sustainable and alternative solutions.

Research has been conducted to incorporate waste in production of masonry (Raut, et al 2011) and insulation blocks .Examples are the use of cigarette butts (Kadir et al., 2011) cotton waste, fly ash (Sarkar et al, 2007). Difficulty in recycling, and harmful health effects of traditional insulation material, specifically fiberglass has started the search for green insulation material. Agricultural materials tried as alternative insulating materials and have been found to have good functional characteristics and environmental safety. These include: material molded from an aqueous mixture of aerogel and gelatin (Carrielee and Simonton, 1997); insulating boards made from the fibers of cotton stalks (Lu et al., 2010); low density insulating boards made from coconut shell and fiber obtained by hot pressing (Fotios et al., 2011); the use of hemp fibers and wood in the manufacture of lightweight composite materials to replace conventional binders such as cement by natural zeolite, which resulted in a material with good mechanical strength and thermal insulation properties (Terpakova et al., 2012), and bio composite material with plaster and date palm for thermal insulation in buildings (Chikhi et al., 2013)

Agricultural wastes can be divided into two categories. Crop residues are remaining after harvesting and byproducts of industrial processing of crops are known as agricultural residue (Aksu et al, 2009). Rice is the primary staple of more than half of the world's population and is harvested in vast areas of the world. Rice is the second largest cereal production in the world according to the Food and Agricultural Organization (FAO). The average annual production of paddy rice around the world was 741.3 million tons in the year 2014. The main by-product of this crop in industrial rice processing is the husk. Rice husks are used commercially and are a key contributor to. It is a fibrous material, with high volume and low density, mainly made of cellulose, lignin, and silica, insoluble in water, with low nutritive properties and weathering resistance. (Gutha et al., 2015). A significant part of the rice husk that is generated is deposited in the soil without any treatment. The environmental impact of this action is that rice husk take about five years to decompose, and a large amount of methane (CH_4) is also generated. Another method of disposal of the rice husks is uncontrolled burning in the open air, which emits large amounts of carbon monoxide (CO) and carbon dioxide (CO_2) ((Khatib et al, 2001)

2.1 Rice Hull Generation:

Rice hull generation as agricultural residue in United States exceeds one million metric tons, and worldwide generation is 100 times of that quantity (Olivier, 2003). Rice hulls has been proposed and tested for thermal insulation purposes in buildings by various researchers (Fotios et al, 2008). The thermal conductivity of rice hull has been measured using equipment built and operated in accordance with ASTM methods and this suggests that thermal conductivities of rice hulls are between 0.046 – 0.057 W/m.K (Vohra et al.,2005). These values prove excellent insulative properties, hence, the incorporation with cement are expected to give a higher thermal resistance than a normal masonry block. Much less density of rice hulls makes the blocks light weight, i.e. less transportation cost. Composite insulation boards, particle boards (Johnson, 2007) has been very useful due to its insulative and sound absorbing properties.

2.2 Cotton byproducts for Building Construction:

Cotton is planted on large scale in some countries like United States, China, Brazil, India, Pakistan, and Australia, due to Industrial demand. The worldwide cotton yield for the year 2016-2015 is 22 million metric tons according to USDA and it is expected to increase by 4 percent. This substantial amount of cotton production leads to the generation of several by-products, which have many industrial uses. Though various researches (Sakli et al, 2008) emphasized on the use of cotton wastes, majority of it is either used for livestock food or burnt, due to lack of economic value. The smoke and carbon dioxide create into the atmosphere creates smog and global warming. Algin and Turgut (2007) made use of an amalgamation of cotton wastes (CWs), limestone powder wastes (LPWs) and a combination wood sawdust wastes (WSWs) to produce low cost and lightweight complex as a structure building material with thermal conductivity 0.22 W/m.k. Cotton wastes generated in the industrial process of washing the cotton after mechanic cleaning and production yarns. According to Sakli et al. (2007) the amount of waste is approximately 6.43% of the treated materials. Depending on the mill, total waste can be 1,143,700 Kg in a working year. These waste fibers, works as good thermal insulator due to the trapped air and natural fibers provide bending strength to the binder material (Binici et al.2011).

A number studies have explored the thermal insulative properties of cotton stalk, the major crop residue of cotton production (Lu, et al, 2009). Binder less cotton stalk fiberboard (BCSF) made of cotton stalks, with no added chemical additives, have experimented to have thermal conductivity range from 0.0585 to 0.00815 w/m.k and a density of 150-450 kg/m3. This value is comparable to the traditional insulations like expanded perlite and vermiculite. The thermal conductivity of cotton stalk is almost double that of traditional insulation materials. Environment friendly Binder-less Cotton Stalk Fiberboard (BCSF) was manufactured from cotton stalk with no chemical additions by Lu et al, (2017). had made use of salvage paper mills waste and cotton waste to fabricate Waste-Create Bricks (WCBs), results indicated that bricks thus formed were thermally stable and meet the complied standard (IS 3495 (Part 1–3): 1992).

2.3 Other Agriculture Waste:

Coconuts, used for food and non-food products are generally grown in the coastal areas of tropical countries. Coconut coir is the major residue of coconut production, which accounts 15-10 million tons of coir out of 40-50 million coconut production (FAO,2003). Coconut coir has been studied for building insulation boards. Study shows thermal conductivity in range of 0.054-0.1854 W/mK. Despite the low strength, the particle board shows low thermal conductivity, which qualify for superior insulation material. According to the FAO, sugarcane was the highest produced crop in the year 2011, with more than 700 million tons of yield. This tropical crop is presently grown in more than 100 countries. The main waste product from sugarcane industry is bagasse, which consists of fibers with a range between 0.156 mm to 0.504 mm (Krishpersad, M., et al., 2006). Bagasse is crushed and squeezed cane stalk of sugarcane. Squeezed juice is processed for sugar production. Bagasse utilized as a raw material for production of soft boards, fiberboards, particle boards and hardboards. Bagasse thermal insulation has thermal conductivity in the range 0.046 – 0.051 W/mK (Manohar, et al., 2006) and has been used as roof insulation in Jamaica, Ghana, and the Philippines (Panyakaew and Fotios 2008)

Corn is the most widely grown cereal crop. In the global production of cereals crops, the maize rank first after rice and wheat. The world production of corn was over 600 million tons in 2003. While the United State produces almost half of the world supply, other major producers are China, Brazil, Mexico, Indonesia, and India. Fiber boards and particle boards made of Corn stalks and cobs exhibits high mechanical strength. The hot-pressed particle boards using corn cob shows a thermal conductivity of 0.096 W/mK (Sampathrajan et al,1992)

3. MATERIALS AND METHODS

Two binders were considered in this study. Cement being a ubiquitous high strength binding material for structural construction was chosen for both masonry and insulation blocks. They were cement and poly vinyl acetate, and water resistant glue. Binder polyvinyl acetate was used only for the insulation prototype, whereas cement was used both structural and insulation material. Polyvinyl acetate (PVA) was an easily available and inexpensive wood adhesive. Properties of masonry blocks with cotton waste, cotton stalks, and rice hulls were investigated. The incorporation of natural fibers in concrete were expected to aggregate reduction and save natural resource.

Three agricultural waste products, were combined with two binders to develop insulative material. Primarily cotton stalk, cotton husk and rice hulls were mixed with polyvinyl acetate (PVA). Prototype blocks were tested for thermal conductivity. Thermal prototypes made of rice hulls, cotton stalks and cotton wastes were generated using glue as a binder. Thermal Conductivity and thermal resistance of each prototype were determined for a temperature differential of 20 F°, as per standard testing protocols. Rice husk, Cotton stalk and Cotton glue materials were mixed and casted at 5%,10%, 25% and 50% weight percentage of the cement. Figure 2-12, Figure 2-13, and Figure 2-11 are pictures of prototypes Rice husk-cement, Cotton stalk-cement and waste cotton-cement from experiment. Figures 1-3. The prototypes of waste cotton-cement showed signs of mold (Figure 2), which can be a great concern of indoor health quality if used in construction, thus this composite was discarded as a possible alternative. Also, it is difficult and non-homogeneous to mix to binder.

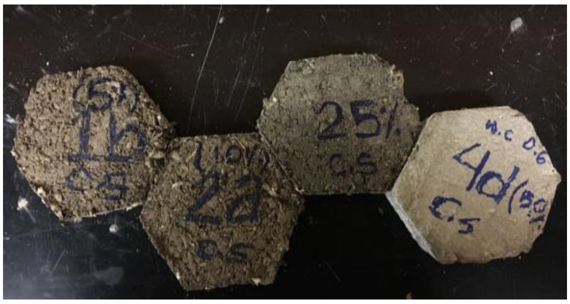

Figure 1: Prototypes made of Cotton stalk-cement

Figure 2 represents the envisioned manufacturing process for the production of cotton stalk-cement blocks for use in temporary housing in the aftermath of disaster.

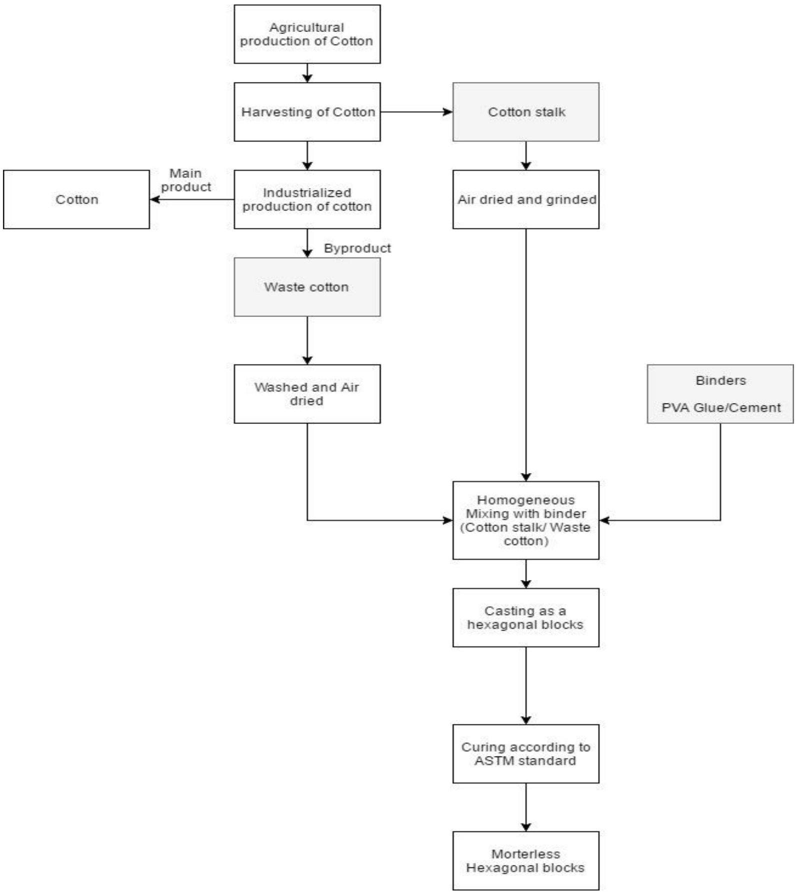

Figure 2:Manufacturing process of hexagonal blocks from cotton stalk and waste cotton

This study also investigated the possibility of agricultural material as part of masonry blocks. These blocks are intended to use as non-load bearing or non-structural members, though reinforcement can be installed by casting holes for reinforcement bars into blocks easily. Though it can be used as structural wall for simple, one storied structures in absence of any reinforced concrete vertical members, due to its high and adequate quality. As most of temporary disaster relief housings were intended to keep simple and one storied. Due to consistent thermal conductivity and superior thermal resistance among three agricultural waste materials, as further described in material selection section rice husks were considered for masonry blocks.

In this study, 1%-10% of replacement by rice husk had been considered while developing the rice husk-cement composite. 4 x8 cylinders are casted with 1%, 2.5%, 5%, 7.5% and 10% weight based rice husk-cement composite.

Figure 3: Cement as Binder: mold formation was observed

3.1: Thermal Conductivity Testing:

Thermal conductivity measures the ability of a material to transfer heat. Measurement of this property is essential for understanding the energy efficiency and thermal performance of the materials. FOX 200 Lasercomp Heat flow meter had been used in this experiment. It utilizes a steady state technique for the determination of thermal conductivity. The Heat Flow Meter Method, is defined by international standards ASTM C518, ISO 8301, and DIN EN 12667. In a heat flow meter, a specimen was positioned between two temperature controlled plates. The user-defined temperature difference (ΔT) between the upper and the lower plates resulted heat flux (Q/A) through the sample. This heat flux from steady state heat transfer was measured by two thin film heat flux transducers that covered the upper and lower sample surfaces (brochure; TA instruments, 2017). The average heat flux was used to calculate the thermal conductivity (λ) and thermal resistance (R), according to Fourier's Law.

Thermal conductivity, $\lambda = Q\,L/\,A\,\Delta T$ (W/mK) (Btu in/h ft2 F) **Equation 1**

Thermal resistivity, $R = L/\lambda$ (m2K/W) (h-ft2 UNITS -F/Btu) **Equation 2**

Where, L is sample thickness and A is the area.

4. RESULTS AND DISCUSSION

Several prototypes were created to determine the optimal design that would produce a prototype that was thermally and environmentally superior to traditional insulation. Three materials mixed with polyvinyl acetate and cement to create an appropriate binder were tested in in various concentrations. They included rice husk, cotton stalk and cotton fibers. Adhesives were mixed and casted at 5%, 10%, 25% and 50% weight of cement to provide structural support. Thermal properties of the materials were tested with upper plate temperature of 80° F and lower plate temperature at 60°F. Test results of thermal resistance (mK/W) revealed that the average thermal resistance of the control mix or cement mix was 2.984 mK/W. Though waste cotton as a component has adequate thermal resistance, while mixed with binder fail to provide consistent result. Cotton stalk-cement and rice husk-cement composite provided higher thermal resistance, with thermal resistance consistently exceeding 118% of the control values. After thorough testing, rice husk-cement composites were selected for further detailed study of thermal and structural properties.

4.1 Insulation Blocks:

Thermal conductivity of waste material-PVA a waste material-cement composites are documented in Table 1-1 and Table 1.2. Figure 2-17 is a graphical representation of the thermal resistivity of the suggested insulation materials, which shows the highest thermal resistance for rice husk-PVA composite. Figure 2-17 shows the highest thermal resistance for rice husk-PVA, which makes it best insulation material among three waste-PVA composite.

Table 1-1: Thermal properties of Rice hulls, Cotton stalks and Cotton waste prototypes with Poly vinyl acetate Glue

Material	Binder	Average thermal conductivity (mk/W)	R value
Rice husk-PVA	Poly Vinyl acetate	0.09	11.11
Cotton stalk-PVA	Poly vinyl acetate	0.15	6.381
Cotton waste-PVA	Poly vinyl acetate	0.10	9.96

Table 1-2 shows the thermal resistance of waste-cement composites and the control mix, which was casted with 100% cement mortar. Rice husk-cement, cotton stalk-cement and cotton waste-cement composites had been casted in 5%, 10%, 25%, and 30% weight based waste percentage ratio for thermal testing. Waste-cement composites showed much lower thermal resistivity than waste-PVA composites. The density of waste-cement composite was higher with respect to waste-PVA composites. Each composite showed higher thermal resistivity than control mix, which has a thermal resistivity of 2.98 W/ mk. 30% Rice husk-cement composite showed almost three (2.64) times thermal resistivity than control mix. Due to inconsistent thermal conductivity and non-homogeneous nature cotton waste-cement composite was not considered for probable insulation material.

Table 1-2: Thermal resistance of Composite materials

Waste-cement material ratio	Rice Husk-cement (mk/W)	Cotton stalk-cement (mk/W)	Waste Cotton-cement (mk/W)
5:95 (5%)	4.0665	3.7085	4.281
10:90 (10%)	4.926	4.736	5.5905
25:75 (25%)	6.8	6.6135	5.8255
30:70 (30%)	7.785	7.318	7.87

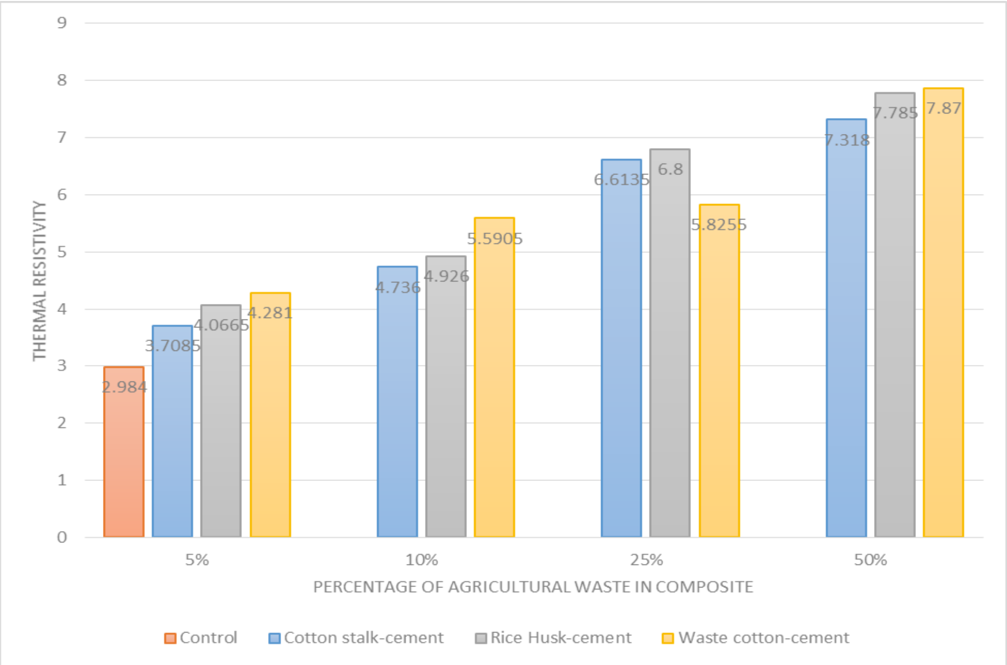

Figure 2-1: Comparison between thermal resistance of cotton stalk, rice husk, cotton waste-cement composite and control mix

5. CONCLUSION

The developed structures are intended to use as non-load bearing or non-structural members, though reinforcement can be installed by casting holes for reinforcement bars into blocks easily. Structural compression testing of casted blocks provided an assessment of design strength. 4 x 8 cylinders were casted with 1%, 2.5%, 5%, 7.5% and 10% rice husk-cement composite and cotton-waste byproduct. The compressive strength of the material was been examined according to ASTM C39/39M - 09a. Results were compared with the control and checked for the minimum required compressive strength for non-structural masonry units. Results indicated that cotton-stalk mix in the percentage of 7.5% provided the optimal level of thermal insulation and structural support.

This cotton-stalk mixture was further assessed through a life cycle assessment. The research team used SimaPro v7.2, and built a cradle to grave model of the developed insulation, and traditional PU foam and fiberglass insulations, and then tested the underlying assumptions of the models. Data was drawn from a combination of literature review, and SimaPro databases including EcoInvent. Mid-point and end-point impact assessment methods were employed, including Impact 2002+ v.2.1 (Jolliet et al. 2003). The life cycle assessment results revealed a 58% decrease in the environmental impact associated with non-renewable energy use when the cotton-stalk mix was compared to traditional PU foam. Also of note is that improved environmental metrics across four key categories: global warming, non-renewable energy, respiratory inorganics and terrestrial acidification/nitrification was observed. The most contributive factor to negative environmental impact associated with the insulation prototype was use of the polyvinyl acetate binder, revealing the potential for prototype design improvement.

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