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Mechanical Properties of Sustainable Adobe Bricks Stabilized With Recycled Sugarcane Fiber Waste

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ABSTRACT
In the pursuit of cheaper and more sustainable building materialsto meethousing demands in developing countries like Cameroun, the mechanicalproperties ofadobe bricks which have been stabilized with recycled sugarcane fiber waste were investigated. Laboratory experiments were conducted using sugarcanefiber waste stabilized adobe brick specimens with fiber proportions of 0%, 0.3%, 0.6%, 1.2%, 2% and 3% by weight.Fiber stabilization increased compressive strength by 58.61% for 3% bricks, reaching 4.79 MPa.Further, 3% fiber stabilized bricks shrunk by 7.49%, while the non-stabilized bricksshrunk by 12.13%. Also, 3% bricks lasted for one week before deterioration when immersed in water, while the non-stabilized bricks lasted for only a few hours. The findings confirmed that sugarcane fiber waste stabilized adobe bricks have improved strength, durability and stability. The use of abandoned sugarcane fiber waste in adobe bricks will contribute to the development of more durable, sustainable and stronger adobe brick structures, as well as reduce the environmental and economic challenges associated with the disposal of sugarcane waste.
Keywords:Adobe bricks, Sustainability, Sugarcane fiber (bagasse), Material properties, Mechanical properties.

I. INTRODUCTION

The Bruntland Commission promotes global sustainable development by emphasizing on the need for current generations to meet their needs without compromising on the ability of future generations to meet their own needs. There is a critical need to develop affordable and sustainable solutionsto provide low-income housing for the world's homeless and poor populations. The high costs associated with purchasing and transporting materials such as cement and iron continue to be a barrier to sustainable housing. As such, there is a critical demand for cheap and sustainable building materials.Various studies have been conducted using environmentally friendly materials and methods to develop sustainable building products. Among the multitude of building methods, earth construction has been studied.

Earth building is the most common method of providing cheap accommodation since soil is readily available almost anywhere on the planet (Namango, 2006). It was estimated by Smith and Austin (1989), that over a third to one half of the world's population live in some type of earthen dwelling.Common earthen building materials and methodsinclude daub, cob, rammed earth, earth sheltering, compressed earth blocks and adobe bricks. Adobe bricks (ABs), also called mud bricks or sun-dried blocks are made by digging earth close to the construction site; mixing it with water, manure, ash or chopped straw; putting the mix in wooded boxes; and then drying in the sun before usage (Khedari, Watsanasathaporn, andHirunlabh, 2005). ABsarecheap, have good insulation properties, contribute feweremissions, and help to promotelocal economies.

Further, Silveira, Varum, Costa and Carvalho (2014) maintained that adobe construction presents a myriad of cultural, social and architectural benefits; however, they are in a poor state of conservation, partly due to the lack of knowledge of the mechanical properties of adobe masonry.The poor durability and strength of adobe bricks reduces its capacity to be an effective sustainable material. There is a dire need to investigate methods to enhance the properties and performance of ABs using environmentally friendly, cost-effective and sustainable materials and processes. Solutions to address these weaknesses have included plastering and drainage at the base of adobe brick walls. In particular, stabilization methods to improve the strength and durability of this material are of interest.Ndigui(2011) and Galán-Marín, C., Rivera-Gómez, C. and Petric, J. (2010) agreed that stabilization should be used to improve soil density, porosity, permeability and mechanical resistance.

Raut, Ralegaunkar, and Mandavegane (2011) provided a comprehensive review of brick stabilizing wastes such as cigarette butts, fly ash, dried sludge, kraft pulp residue, crumb rubber waste, waste tea, petroleum effluent treatment plant sludge, and welding flux slag. Azeko, Mustapha, Annan, Odusanya and Soboyejo (2015) found that laterite bricks stabilized with 20% polyethylene by volume had the best combination of compressive strength and fracture toughness. Compared to the traditional bricks (0.5 – 1 N/mm^2), Binici, Aksogan and Shah (2005) concluded that stabilization with plastic fibers, straws and polystyrene fabrics improved the compressive strengths of fiber reinforced mud bricks (3.7 – 7.1 N/ mm^2).Further, Binici et *al.* (2005) explained that these fiber reinforced bricks had lower dead weight leading to lower material handling costs. Sutcu and Akkurt (2009) reported that porous earthenwarebricks stabilized with paper processing residues (30%)had a 50% reduction in thermal conductivity and higher compressive strengths.In their study incorporating cotton and limestone powder in a brick material, Algin and Turgut (2007) obtained improved flexural strength (2.19 MPa), compressive strengths (7 MPa), water absorption, and energy absorption.Rahman (1988) found that rice husk stabilized bricks had improved compressive strength, water absorption, and linear shrinkage.Few studies have explored the use of sugarcane fiber waste in stabilizing bricks using conventional, sustainable and cost-effective methods that are most familiar to the indigenous populations in developing countries.

Sugarcane is the most important agricultural crop production in the world with 1900 million tons cultivated on 27,181,580Hectares in 2014; and thus approximately 20% of the global agricultural production (Food and Agricultural Organization, 2016). Sugarcane grass is a renewable, natural agricultural resource and provides sugar, besides a myriad of products with ecological sustainability. The sugarcane bagasse is the dry, pulpy, fibrous matter that remains after the crushing of sugarcane stalk during juice extraction.The sugar industry produces 30% of bagasse for each lot of crushed sugarcane - for each 10 tons of sugarcane crushed, a sugar factory produces nearly 3.3 tons of bagasse. Since bagasse is a by-product of the cane sugar industry, the quantity of production in each country is proportional to the quantity of sugarcane produced. Despite the large quantities of production, the utilization of sugarcane bagasse is still limited and mainly used as a fuel to power the sugar mill. The use of this locally available, cheap raw material (waste)in adobe brick production could contribute to advancement of sustainable building materials to provide cost-effective housing solutions in developing countries such as Cameroun.

The problem of this present study is to investigate the physical and mechanical properties of recycled sugarcane waste fiber reinforced adobe bricks. The primary research question is whether the use of sugarcane waste fibers can improve the mechanical properties of adobe bricks. The research hypothesis is that the addition of recycled sugarcane waste fibers will improve mechanical properties of adobe bricks.The specific objectives are to determine if Sugarcane Fiber Stabilized Adobe Bricks (SFSAB):

(1) have a higher compressive strength compared to non-stabilized adobe bricks;
(2) absorb less water and can last longer in water compared to non-stabilized adobe bricks;
(3) have an improved resistance to shrinkage compared to non-stabilized adobe bricks.

Soil as a Building Material

Soil is a loose material of varying thickness, which supports vegetation and bears humanity and its structures (Houben and Guillaud, 1994). The benefits of soil as building material are as follows:availability in large quantities (Adam andAgib, 2001);economically beneficial (Minke, 2006);environmentally sustainable (Easton, 1998);easy to design with and high aesthetical value (Morton, 2007);suitable for construction of most parts of a building (Stulz, 1988);fire resistant(Hadjri, Osmani, Baiche, and Chifunda, 2007);improves indoor air humidity and temperature (Minke, 2006); saves energy (Morton, 2007); and requires simple tools and less skilled labor (Easton, 1998); suitable for very strong and secured structures (Lal, 1995);provide better noise control (Hadjriet *al.*, 2007);unlimited reusability of the non-stabilized soil (Stulz, 1988); absorb pollutants (Minke, 2006).Its disadvantages include: extensive water absorption (Stulz, 1988); poor resistance to abrasion and impact (Stulz, 1988); low tensile strength(Lal, 1995);high maintenance (Hadjri et *al*., 2007); and suitable only for in situ construction (Walker, Keable, Martin, and Maniatidis, 2005).

The widely used techniques in earth construction include rammed earth, straw, clay, wattle and daub, shaped earth, extruded earth, cob and compressed earth and adobe (mud) bricks.Adobe bricks are among some of the first building materials developed by man. The soil suitable for producing good bricks should have sand (55-75%), silt (10-28%), clay (15-18%) and organic matter (0-3%). When these proportions are ignored, an increase of cracks in the bricks will be observed. Generally, soil properties may be improved through soil stabilization. Houben and Guillaud(1994) noted thatthe stabilizationof soil will modify the properties of a soil-water-air system inorder to obtain lasting properties which are compatible with a particular application. The primary goal ofsoil stabilization is to use physical and chemical processes to improve soil properties so that they are better able to resist unfavorable physical conditions.Galan-Marin, Rivera-Gomez and Petric (2010) confirmed that soil stabilization with natural fibers improved the mechanical properties of clay bricks, in particular the compressive strength. In this present study, the physical and mechanical properties for adobe bricks stabilized with recycled sugarcane fiber waste were investigated.

Sugarcane Fiber Waste as a Building Material

The sugarcane wastes also referred to as bagasse, is the fibrous matter that remains after sugarcane stalks are crushed to extract their juice.Fibers are characterized by their length being much greater compared to their cross-sectional dimensions. Sugarcane belongs to the grass family and grows up to 6 m high and has a diameter up to 6 cm. The cane basically consists of juice and fibers (Santaella, 2007), and its average composition is as follows: water (65–75%), sugars (11–18%), fibers (8–14%) and soluble solids (12–23%).The sugar cane bagasse has the following composition by weight:cellulose (41.8%); hemicellulose (28.0%); lignin (21.8%)(Bilba et *al.*, 2003).Agopyan (1988) presented several propositions involving the use of pressed sugar cane bagasse for the production of panelsand sheets.Onchiri, Kiprotich, Sabuni, and Busieney(2014) increased plasticity and compressive strength of earth blocks, after replacing cement with sugarcane bagasse ash. Alavéz-Ramírez, Montes-García, Martínez-Reyes,Altamirano-Juárez, and Gochi-Ponce (2012) used sugarcane bagasse ash and lime to improve the durabilityand mechanical properties of compacted soil blocks. The results indicated that blocksmanufactured with 10% of lime in combination with 10% of sugarcane bagasse ash showed better performance than thosecontaining only lime.Ghazali, Azhari, Abdullah, andOmar (2008)found that composites with sugarcane fibers exhibited the greatest tensile strength with good hardness properties. While several studies focused on sugarcane ash, no study was found to investigate the physical and mechanical properties of sugarcane fiber reinforced mud brick using the indigenous methods familiar to the natives of Cameroun.

II. EXPERIMENTAL MATERIALS AND METHODS

Materials

The experimental materials used in this present study were soils, water and recycledsugarcane fiber waste from Bambili in the Northwest region of Cameroun. The soils were collected from Bambili which is about 1300m above the sea level. The soil was taken 50 cm below the natural ground level in order to avoid soils rich in organic matter.The absence of the musty smell confirmed that the soil was suitable for the production of adobe bricks as it did not contain organic matter. When moistened the soil becomes plastic and sticky when touched, suggesting that the soil was clayey(HoubenandGuillaud, 1994). Further a sedimentation test revealed a higher percentage of clay and silty, confirming that the soil was clayey, silty or the combination of the two making it suitable for the production of good adobe bricks.Clean water for mixing bricks was obtained from public water system at a temperature of 20ºC. Thesugarcane fiberswere obtained after manual extraction of juice from sugarcane plants (Figure 1) grown in Bambili and its surroundings areas.

Fig.1. Sugarcane Plant

Fig. 2. Sugarcane wastes

Methods

After extraction of the juice, the pith and stalks of the sugarcane were collected and exposed tothe sun for two months (Figure 2).After drying in the sun, the fibers were soaked intap water for a few minutes to prevent deterioration. The fibers were then dissociated from each other to obtain finer fibers.The dimensions of these fibers varied approximately from 0.2 to 1.0mm in diameter, and 10 to 50 mm in length. The fibers were then dried and weighed into the appropriate adobe brick mix proportions.

Following the preparation of the materials, the soil quantities were measured and the sugarcane waste fiber added using the following percentages of sugarcane fibers for different mixes: 0%, 0.3%, 0.6%, 1.2%, 2%, and 3%. For each mix type, 12adobe brick specimens were produced (8 for the compression tests and 4 for water absorption tests). It must be noted here that the non-stabilized bricks had 0% fiber. Water was then measured and added to the dry materials. A total of 72 bricks were manufactured using 120×60×60 mm brick molds.As shown in Figure 3, the bricks were then cured in a shaded area to avoid direct sunlight and thus minimize the incidence of cracks in the bricks.

Fig. 3. Recycled sugarcane fiber waste bricks

The bricks werecovered for one week and then allowed to cure for 28 days at ambient temperature (20 to 26ºC), after which the bricks were taken to the laboratory for testing.

Laboratory Tests

Laboratory tests were conducted to determine the shrinkage, compressive strength and water absorption properties of thestabilized and non-stabilized adobe bricks.

Shrinkage Test

The Shrinkage Test was used to determine the extent to which the sugarcane fiber waste stabilized mud bricks were subject to withdrawal after drying. The key equipment needed was the ruler. After manufacturing each brick, its three dimensions (length, width and height) were measured. The bricks were then allowed to cure on a flat surface at ambient temperature in a shaded area. After drying, the three dimensions of each brick were measured again and recorded for calculating the Reduction in Volume (RV) Percent using Equation 1:

$$RV = \frac{Vw - Vd}{Vw} \times 100 \qquad \text{Eq. 1}$$

Where: (Vw)= Wet Volume, (Vd)= Dried Volume RV = Reduction in Volume (%)

Compression Test

The Compression Test was used to determine the compressive strength of the bricks, as well as describe the behavior of the adobe bricks when subjected to compressive load. The equipment included the compression machine and metallic plates to surmount the compressive plates. The brick specimens were mounted on to the compression equipment and the compressive load was increased at 0.05mm/S until the block fractured. The bricks were crushed flat in the same position as they would be in construction. The compressive strengths of the adobe bricks were calculated using Equation 2.

$$\sigma = F/S \qquad \text{Eq.2}$$

Where: σ = compressive strength; **F** = maximum load applied before failure;
S = cross sectional area of the specimen

The Water Absorption Test by Capillarity

The Water Absorption Tests by Capillarity were conducted to measure the water absorption properties of the adobe brick specimens. The equipment and materials neededincluded an open flat-bottomed bucket, a ruler, a balance and a stop watch. The bucket was filled to a height of height of 5mm and the bricks were placed in the water, after weighing the blocks. After one hour, the bricks were removed and weighed again. The ratio(W_a) of the dry mass (M_d) over the humid mass (M_h) was computed for each sample using Equation 3.

$$W_a = M_d / M_h x\ 100 \qquad \text{Eq. 3}$$

The Water Absorption Test by Immersion

The Water Absorption Test by Immersion was used to determine the extent to whichthe adobe bricks can resist water penetration. The equipment included the flat-bottomed bucket, clean water, and a stop watch.The bucket was filled with clean water, after which the adobe brick was totally immersed in water. The behavior of each brick specimen was checked after1 hour, 2 hours, 12 hours, and 24 hours.The time taken for each brick to deteriorate due to water absorption was recorded.

III. RESULTS AND DISCUSSIONS

Soil grain size analysis showed that the soil content was as follows: Gravel (2%); Sand (43%); and Silt and Clay (55%). Applying the findings on the soil classification by the Unified Soil Classification System (USCS) and American Society for Testing Materials (ASTM) Standards**,** the soil can be considered as sandy silty clay. This provides the required evidence that the sample soil chosen can be used for the production of adobe bricks.Also, following Spence and Cook (1983), this is a good soil for stabilization purposes**.**The results obtained from the shrinkage test, the compression test and the water absorption test are discussed in this section.

Shrinkage Test

The results for the shrinkage tests are shown in Figure 4. The diagram shows the shrinkage with respect to the percentages of sugarcane fiber waste in each adobe brick mix.

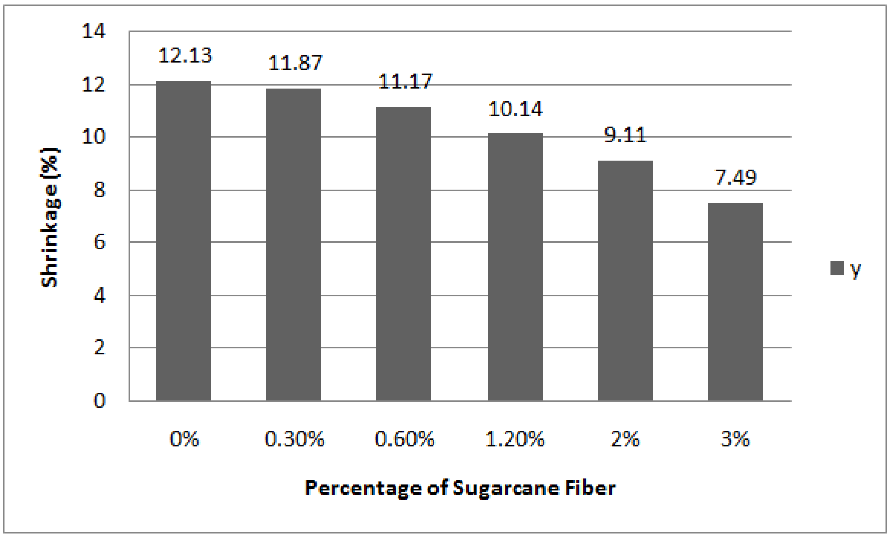

Fig.4. Shrinkage percentage bysugarcane fiber mix.

Figure 4 revealed that while non-stabilized brickswere characterized by shrinkage of 12.13%, the 3% fiber mix bricks had less shrinkage (7.49%). There is a progressive reduction of the shrinkage percentage as the percentage of sugarcane fiber increased from 0% to 3%. These results providestrong evidence that stabilizing adobe bricks with recycledsugarcane fiber waste increases the stability of the adobe brick as there is a reduction in shrinkage percentage. Stabilized adobe bricks are less influenced by the clay shrinkage, in particular the 3% mix. The use of the 3% brick mix reduces shrinkage by 60.89%, making the 3% mix, the optimum adobe mix.

Compression Test

The compression test provides an indication of the strength of the sugarcane fiber waste stabilized adobe bricks. The results from the compression tests for each sugarcane fiber mix are shown in Figure 5.

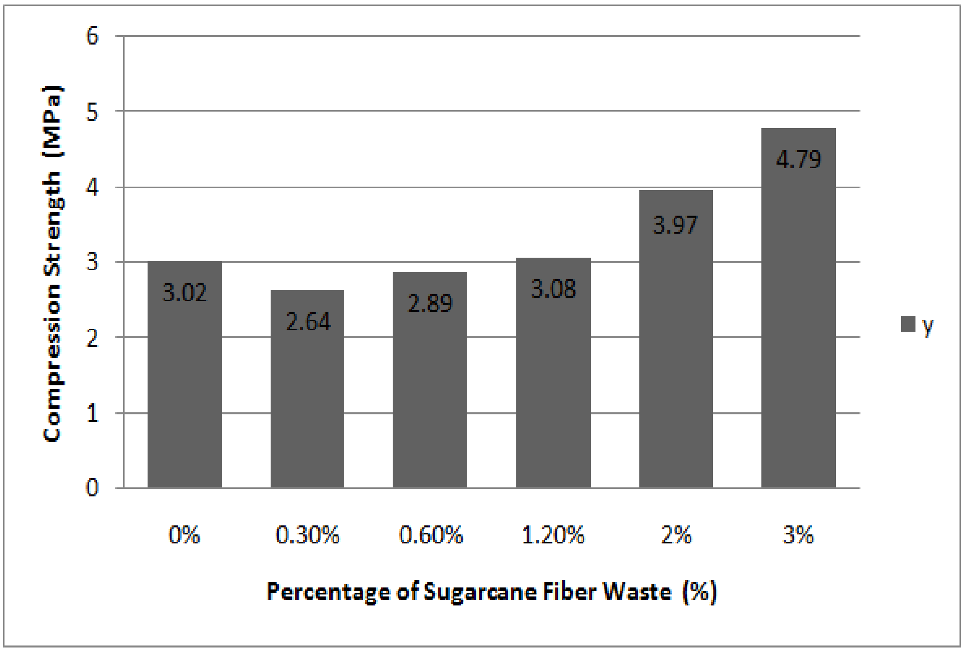

Fig.5. Compression strength by percentage of sugarcane fiber waste

From the Figure5, it can be noticed that there is initially a reduction in compression strengthfrom 3.02 MPa to 2.64 MPa.The reduction of compression strength is because the percentage of fiber stabilizers were not enough to stabilize the adobe bricks, but instead disturbed the texture and the bonds between the soil particles and weakened the adobe brick.After the lowest compressive strength of 2.64 MPa at 0.3% fiber concentration, the compression strength increases continuously to 4.79 MPa for the 3% fiber mix bricks. It is thus obvious that the addition of recycled sugarcane fiber waste improves the compression strength of adobe bricks, at a fiber concentration of 1.2% or more. The increase in strength couldhave been due to the creation of isotropic matrix between the claystructure and the sugarcane fibernetwork; such a matrix would oppose movement of particles and create stability mainly because fibers appear to distribute tension throughout the bulk of material.Considered at the level of apotential crack,Houben andGuillaud(1994)explained that the fibers oppose the formation of a crack in step with the increase inthe stress.

Spence and Cook (1983) presented an average brick strength range of 3.0 - 3.5 MPa for load bearing requirements of normal two-story buildings. Consequently, the recycled sugarcane fiber waste stabilized bricks can be used for load bearing or structural walls. The results confirmed the hypothesis that sugarcane fiber waste stabilized bricks have improved mechanical properties and can be adopted for important construction work, especially the 3% fiber mix.

Water Absorption by Capillarity

TheWater Absorption Test by Capillarity provides an indication of the moisture resistance properties of the brick. The results are shown in Figure 6 which shows the different percentages of water absorbed by capillarity after one hour of immersion for the different fiber mixes.

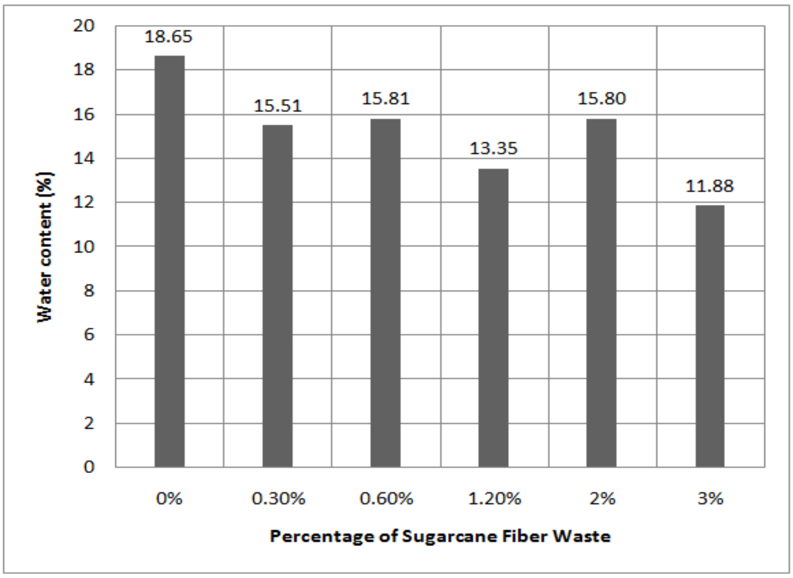

Fig.6. Water absorption percentage by percentage of sugarcane fiber waste

The Water Absorption Test failed to establish any significant conclusion as no specific patterns were demonstrated in the data plotted (Figure 6). The non-stabilized bricks possessed the highest order of water content after one hour (18.65%), while the 3% fiber stabilized brick had the lowest water content after one hour (11.88%). However, there is not a regular progression in the regression of the water content as the stabilizers are added. In between these extreme points, a serrated path existed. This could be due to handling or processing errors. These results make it difficult to make any significant conclusions on the moisture absorption characteristics of recycled sugarcane fiber wasteadobe bricks.However, in general the results show that fiber reinforced bricks perform much better in resisting water penetration, compared with non-stabilized brick. Additional water penetration tests such as water test by submersion were conducted to provide some clarity to these inconclusive results.

Water Absorption by Submersion

The Water Absorption by Submersion Test measured the durability of stabilized and non-stabilized adobe bricks when exposed to flooding. The criteria for the evaluation of brick deterioration were determined as negligible, light, moderate, and severe. Chen (2009) listed the visual descriptions at the various levels of deterioration as follows:

- Negligible: the brick does not exhibit any visible damage. No indentations occur with the pressure of one finger.
- Light: the brick does not exhibit any visible damage, but indentations occur with slight pressure.
- Moderate: the brick shows visible deterioration and indents with slight pressure. The water remaining in the container is brown due to brick decomposition.
- Severe: the brick loses most of its surfaces or edges. The water is brown and muddy from erosion, and the brick cannot withstand any pressure.

Following Chen (2009), Table 1 provides a description of the level of deterioration for each of the different sugarcane fiber mixes. The deterioration of the bricks was evaluated after one hour and after 24 hours. The time was extended for thebricks that presented no sign of deterioration until they presented some signs of deterioration.

Table 1. Level of Brick Deterioration by Fiber Mix Percentage.

Duration	0%	0.3%	0.6%	1.2%	2%	3%
After 1 hour	Moderate	Negligible	Negligible	Negligible	Negligible	Negligible
After 24 hours	Severe*	Moderate	Light	Negligible	Negligible	Negligible
After 48 hours	Severe*	Severe*	Severe*	Moderate	Negligible	Negligible
After 72 hours	Severe*	Severe*	Severe*	Moderate	Moderate	Negligible
After 5 days	Severe*	Severe*	Severe*	Severe*	Light	Light
After 10 days	Severe*	Severe*	Severe*	Severe*	Severe*	Moderate

*Total brick

**No sign of deterioration

From Table 1, it is obvious that the resistance of adobe bricks to water submersion (flooding) improved with increments in the percentage of sugarcane fiber content in the adobe bricks. Generally the non-stabilized brick did not last for more than 2 hours when submerged in water, while the3% sugarcane fiber stabilized bricks lasted more than 72 hours without any visible deterioration. It should be specified that, due to time constraint, the test was stopped after 10 days of submersion. The non-stabilized adobe bricks started deteriorating in less than one hour after immersion. Its degradation was completed after 2 hours and 30 minutes of immersion in water. After 24 hours of submersion, fiber stabilized bricks at 0.3% and 0.6% started deteriorating with visible signs, although the mixes with 1.2%, 2% and 3% fiber stabilized bricks were still intact and undisturbed. The adobe brick with the 1.2% fiber completely deteriorated after 72 hours.

The bricks that performed the best had the 2% and 3% mix. The experiment showed that those bricks can last for more than three days when entirely immersed. The 3%brick was still stable even after 5 days with just some light indentations when pressed with the finger. On the 10^{th}day the experiment was stopped. Although the degradations were severe for the 2% fiber stabilized brick, there was no sign of deterioration after 10 days of immersion. The bricks had still preserved their shape, and the water in the bucket was not corrupted.

It can be concluded that sugarcane waste fibers improve the resistance of the adobe bricks against the action of water. This strength could be explain by the fact that the bonds created between the fibers and the soil particles are more much stronger than those between clay and the other particles, conferring strength to bricks which were immersed in water. This explanation can be supported by the fact that the bricks preserved their structure, even when weakened.

IV. CONCLUSION

Raw soil as a construction material has generated renewed interest primarily because of its availability, low cost and compliance with global sustainability goals.In order to improve the mechanical properties of adobe bricks, an investigation was conducted to assess the mechanical properties of sugarcane fiber waste stabilized adobe bricks. As a vegetable, the sugarcane fiber (bagasse) is an entirely biodegradable natural resource which is available in large quantities all over the world.

The tests confirmed that the addition of sugarcane fiber waste to adobe bricks improved its compression strength, resistance to moisture penetration, shrinkage and durability. The bricks with 3% sugarcane fiber by weight had the best properties with the highest compression strength (4.79 MPa). The water submersion test revealedthat the addition of sugarcane waste fibers reduced adobe brick sensitivity to water because while the non-stabilized adobe bricks lasted only two hours before total deterioration, the 3% fiber stabilized bricks lasted for more than one week. The optimum values were obtained for the bricks with 3% sugarcane fibers. However, further tests should be carried out in order to determine the maximum content of sugarcane fiber beyond which the mechanical properties of sugarcane stabilized adobe bricks will start to decline.

Recycling abandoned sugarcane fiber waste for the manufacture of adobe bricks will reduce the environmental and economic challenges associated with the disposal of sugarcane waste. Also, the improved sugarcane fiber stabilized adobe bricks will contribute to the production of more durable and sustainableadobe brick structures. In the long term, the diffusion of sugarcane fiber waste stabilized bricks should contribute to the advancement of global housing sustainability goalsleading to reductionsin environmental deterioration.

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