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Alternative clay bricks inspired from termite mound biomimicry

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ABSTRACT

As the world is witnessing vast pollution during material production, construction and demolition processes of buildings there is a need to seek for alternative materials that will reduce the environmental impact. The present study borrows inspirations from termite's technique to create a material for constructing a naturally cemented mound structure. The studied termite mound was built from a mix of soil particles and termites saliva containing mucopolysaccharides and cellulase enzyme that digests cellulose into beta-glucose or shorter polysaccharides and oligosaccharides. These polysaccharides are found to be a source of soil stabilization and gluing property. In the process to mimic termites' activities clay bricks were produced from a mix of clay soil and cassava flour in a form of hot cassava paste as a source of polysaccharides at 1.5%, 3%, 4.5% and 6% weight of soil. Brick samples created presented an optimal value at 1.5% cassava flour with compressive strength higher than that of burnt clay bricks at 4.28 MPa.

1. Introduction

The choice of materials in building construction is mainly a factor of availability, climatic conditions and cost. As a result, clay has become one of the most commonly used building materials in developing countries despite its association with low structural strength. On the course to improve clay bricks properties kiln firing is used [1], however, this process is linked to massive negative environmental impacts and people's health [2,3]. An empirical comparative study of the environmental impact of sun dried bricks and fired bricks throughout their respective life cycles conducted in Egypt [4] shows that there is a massive difference to the embodied energy and embodied carbon between the two with fired bricks having higher impact to the environment and higher costs. A study conducted in Uganda and Tanzania also came to the same conclusions [5] showing that traditional manufacturing process of fired bricks using small and medium sized kilns in the two countries is associated with excessive energy waste and high costs related to energy and transportation.

With this background, a need for environmental friendly construction material with enough structural integrity arises. The ideal material to be used should be earth based due to availability [6], locally sourced [7,8], and should be able to offer an opportunity for incremental construction since the majority of low/middle income households in developing countries build incrementally [9,10]. A good example of naturally occurring clay structure that fits the three named characteristics with good structural strength and minimum impact to the environment is found in termite mounds.

Studies show that termite mound soils have traditionally been used as construction material for many years in a form of bricks whilst others have been combined with stabilizers such as cement and fibers for construction of adobe structures [11]. However, the challenge of using soils from termite mound to create a construction material is in its limitation in availability. Therefore, this paper

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owes its inspiration from the hypothesis that termite mounds are hard earth-cemented structures and can be mimicked to produce alternative clay-based construction material. Thus, based on the principles of bionic architecture the process will involve studying termites' preparation of soil for construction and mimicking the same with other available soil.

Termites are of about 2800 species and largely found in the tropical and semi-arid regions. They feed on cellulose material from plants and live on soil mounds that they build above or underneath the ground [12,13]. These soil mound structures serve as housing to protect termites and provide food from cellulosic materials [14,15]. In Tanzania most termite species are found in the northern zone and few in the southern zone of the country. Termite mound size can reach up to 20 m wide and 5 m high depending on the climate, termite specie, soil type and depth. In the process of mound construction, termites do not alter the chemical composition of the soil, rather they change its structure by adding their saliva that contains mucopolysaccharides with amounts of cellulase enzyme that converts cellulose into the simple monosaccharide glucose [16]. Before breaking to glucose, cellulose is digested into shorter polysaccharides and oligosaccharides that act as a source of soil stabilization and gluing property in termite mounds construction [17]. Polysaccharides are found in a variety of starchy foods like grains, rice, cassava, potatoes, yams etc.

For the purpose of mimicking termite mound in this study, cold-water soluble cassava flour is used instead of cellulose although they are fundamentally different polymers. This is because the oligosaccharides of starch and cellulose both produce glucose when split [18]. Moreover, due to ease of availability, reduction of costs and in order to understand the potential of using non-industrialized, locally available materials for construction, cassava starch was used. Cassava flour is produced by drying and grinding of cassava roots from a perennial woody shrub with tuberous roots called cassava in the family Euphorbiaceae. Starch is the major component of the cassava roots and can amount up to 80% of the dried weight of the root in some cases [19]. Cassava is highly tolerant to drought and harsh climatic conditions, and is admirably productive on poor soils and marginal lands [20,21]. Additionally, cassava starch was selected for this study due to its proven thickening and stabilizing properties in the food industry [20,22]. Various studies have also shown that it can be used as a rheology modifying agent in concrete, where it can have both plasticising and thickening properties [18, 23–25].

2. Methodology and materials

2.1. Soils collection and preparation

For this study, two types of soil samples were collected from Chunya district of latitude 8°28`31.70`` and longitude 33°23`09.23`` in the southern zone of Tanzania. The termite mound sample is herein referred as "Termite Mound Soil Sample (TMSS)" and the other sample not from the termite mound as "Other Clay Soil Sample (OCSS)". The two soil samples were collected to study the difference if any, due to termites' action or other factors. Soil OCSS was set as the control soil sample and later used to produce new modified clay material that mimics termite mounds (Fig. 1). The active termite mound was excavated at one-meter depth to collect soil with minimum humus. Soil samples were collected in a form of large blocks and granules packed in sisal fiber bags and polyethylene bags. The same depth was excavated on the other clay soil. Both collected soil samples were then transported for laboratory tests and experimentation.

The samples were oven dried at 105 °C with initial weight recorded after every 12 h until no change in weight was observed due to moisture loss in preparation for chemical and physical characterization.

2.1.1. Chemical characterization

In order to understand the chemical composition of the two (2) samples and their variation if any due to termite action, chemical composition analysis was done through X-Ray Fluorescence (XRF) machine and the results are given in Table 1.

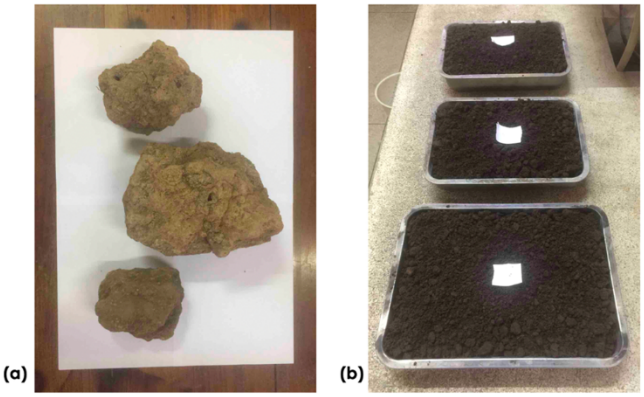


Fig. 1. Soils samples. (a) From termite mound, (b) other clay soil.

Table 1
Chemical composition of the TMSS and OCSS soil samples.

Elements	TMSS (%)	OCSS (%)
SiO_2	67.27	76.45
Al_2O_3	22.83	15.93
Fe_2O_3	2.93	1.95
Na_2O	1.85	2.77
CaO	1.58	0.54
MgO	1.54	0.66
K_2O	1.19	1.12
TiO_2	0.48	0.39
Cr_2O_3	0.11	0.10
P_2O_5	0.07	0
MnO	0.05	0.04
Cl	0.04	0
ZrO_2	0.03	0.03
SrO	0.01	0.01
Rb_2O	0.01	0
Sc_2O_3	0	0.01

2.1.2. Physical characterization

Physical characterization involved determination of various properties including natural water content, particle density and Atterberg limits analysis (liquid limit, plastic limit, plasticity index and consistency index) for both samples (Table 2). The physical characterization of soil for density and Atterberg limits was done according to the British Standard (BSI, 1990) – Part 2: Method of Test for Soils for Civil Engineering Purposes [26].

2.2. Termite mound mimicking

2.2.1. Material preparation and recipe making

The materials used were pure cassava flour, distilled water and clay soil obtained away from the termite mound (OCSS). The preparation of cassava to be mixed with soil involved indirect heating to increase viscosity and cohesive property of the starch molecules through mixing it with hot water [27]. The water molecules become less free and so combine with starch molecules increasing the cohesive forces of paste. During the cooling process, the starch molecules rearrange to form a sticky paste. Prolonged cooling causes stronger bonding within molecules at the availability of water, which ultimately further hardens the paste [28].

A total weight of 800 g distilled water was prepared to be added to the cassava flour to produce paste. 200 g of cassava flour was mixed with a small amount of the 800 g prepared distilled water at room temperature to produce cassava paste. The rest of the water was boiled and added to the cassava paste to avoid clotting of the cassava. A total weight of 4.8 kg of oven-dried soil obtained away from the termite mound is mixed with 1.38 kg of distilled water at room temperature followed with an addition of the hot cassava paste. Wet soil and cassava paste were mixed by hand similar to the way clay bricks are traditionally made in Tanzania. This process was done fast to avoid uneven mixing and cooling of the hot cassava paste. Continuous hand mixing was done until the whole mix reached room temperature.

2.2.2. Sample preparation

For brick preparation, molds of size 70 mm × 70 mm × 70 mm were used to cast a total of 45 samples from soil mix and hot cassava paste at different ratios. Five samples for shrinkage test were cast on 25 mm × 25 mm × 285 mm molds. Both mould types were made of steel with the inner surfaces oiled and then watered to avoid surface sticking. The amount of cassava flour in the hot cassava paste added to wet soil was proportioned at 0%, 1.5%, 3%, 4.5%, and 6% of the weight of soil. Bricks made with 0% of hot cassava paste were not only used as control samples but also to study the mechanical properties of clay soil away from the termite mound.

All samples were left in the molds for three days until set, and then removed and left to air-dry for 28 days until no further change in weight was recorded to ensure no moisture content is retained in the bricks. From observation, an increased amount of cassava-paste beyond 6% added to wet soil caused cracking and development of fungi around the brick surface. It was hypothesized that it was

Table 2
Properties for both soil samples.

Character	TMSS	OCSS
Natural water content, (W) %	8.3	19.6
Particle density, (Pd) g/cm^3	2.66	2.66
Liquid limit, (WL) %	34.7	21.7
Plastic limit, (WP) %	24.1	16.9
Plasticity index, (Ip) %	10.6	4.8
Consistency index, (Ic)	3.27	4.52

caused by cassava fermentation that produces gases and hence swelling of the brick.

2.3. Testing

2.3.1. Compressive strength

Since bricks are used to construct load bearing walls and columns, the compressive strength test was done to study the capacity of the bricks to withstand compressional loads. Moreover, termite mound blocks were tested for compressive strength in order to establish the strength of the natural mound. The natural termite blocks collected from the termite mound were oven dried at 105 °C to remove all moisture content then shaped into specimens of 55 mm × 60 mm × 60 mm in dimensions. When crushing the mound specimen, the load was applied on the 55 mm × 60 mm plane. The compressive strength test was performed according to BS-EN 12390-3: Testing hardened Concrete – Part 3: Compressive Strength of Test Specimens [29]. The test was performed using a compression-testing machine at a maximum loading rate of 1.0 MPa s until the sample collapsed. The same procedures were done to the brick samples produced from both the crushed termite mound soils and the soils with cassava paste.

2.3.2. Linear shrinkage test

Shrinkage is determined by the change in the length of the samples using a dilatometer tool. Linear shrinkage test is aimed at studying the potential cracking of the bricks when drying. Although the standard is specifically designed for hardened hydraulic cement mortar and concrete, ASTM C 157 [30] was adopted to determine the drying shrinkage of the materials used for production of the bricks.

2.3.3. Abrasion test

This test explains the durability of the material against erosive forces. Samples are put into the abrasion resistance machine for 352 revolutions with under laid abrasive sand. The test was performed as per BS EN 1338 – Concrete paving blocks requirements and test methods standard [31].

2.3.4. Water absorption

This test was done to understand the ability of the material to prevent absorbing undesired moisture from the environment. In the process to test for water absorption, samples were coated with silicon sealant on four sides leaving the two opposite sides naked. Water makes contact with one side only, which is considered the exterior surface and the other as the interior surface. The samples were partially immersed in water by 10 mm depth and weighed in every five minutes for half an hour then in every fifteen minutes for another half hour.

3. Results and discussion

3.1. Chemical characterization

The technique used was Analysis of Variance (ANOVA) and found that there is a similar chemical composition with differences in quantities of the elements TMSS and OCSS samples. Both soil samples have the same few mineral elements appearing in large quantities and several in minor quantities. The major mineral elements seen are SiO_2 and Al_2O_3, which is an indication of high content of clay.

3.2. Physical characterization

3.2.1. Natural water content and particle density

Although sampling was done during the rainy season, both soil samples were deduced to have low water content with variation in quantity. The termite mound soil sample had relatively lower moisture content than the nearby clay sample. The difference in natural water content between the two soil samples indicates that termite mound soils are either less permeable due to its cementation property or lose moisture faster than the other. Moreover, both soil samples have equal particle densities of 2.66 g/mm^3 implying that there is similar mineral composition and weight.

3.2.2. Atterberg limits

The liquid limit of the soil sample from the termite mound appears to be slightly higher than that of the soils away from the termite mound. This may be attributed to the presence of high content of clay together with organic materials due to cellulose material decomposition by termites' action. The plastic limit of the termite mound soil is also higher than the other soil due to higher presence of fines. Higher plasticity implies fewer voids and more workability in construction. Higher plasticity implies fewer voids and more workability in construction. A higher plasticity index (PI) in the termite mound soil implies that the soil has a high amount of clay, can hold high amount of water while at plastic state and has high compressibility and drying shrinkage potential. The values of the limits samples used are shown in Table 2.

3.2.3. Particle size distribution

The results of sieve analysis show that sample TMSS has more content of finer materials than sample OCSS. These statistical data

imply that termites randomly select clay and silt for mound construction. The particle size distribution results were used to classify the soil samples where the soil from the termite mound was classified as Clayey soil of Low Plasticity (CL) and the other as Clayey Sand of Low Plasticity (SCL) [21] (Fig. 2).

3.3. Compressive strength

From the results (Table 3), it was deduced that the natural termite mound cubes appeared to have an average compressive strength of 0.76 MPa, which is weaker compared to universal standard sun-dried bricks that has strength in the range between 1.5 MPa and 2.5 MPa or the common burnt brick of 3.5 MPa [27]. These results may be due to various factors that have affected the strength of the mound blocks such as high porosity [32] micro cracks formed from vibration during excavation, transportation and when resizing natural termite mound blocks into cubes.

Due to the above results there was a need to produce bricks from termite mound soil and test for their mechanical properties. The same compressive machine and loading rate was applied to give the results below (Table 4).

An average of 2.92 MPa was deduced from the tests showing lower compressive strength compared to burnt brick. Tests were also carried on to the secondary bricks with added cassava paste to give the results shown in Fig. 3 below.

These results showed an increasing compressive strength with increased cassava paste content to a maximum average of 4.28 MPa at 1.5% cassava flour, which is higher than that of both termite mound bricks and burnt bricks. However, the increase in the amount of cassava paste is hypothesized to increase the occurrence of fermentation that produces gas, making the alternative bricks to swell and consequently causing cracks and weakening the compressive strength as experienced with alternative bricks at 3%, 4.5% and 6% cassava flour. Moreover, this result give an indication that the structural integrity of termite mounds is caused by the live action of termites which was mimicked by addition of hot cassava paste to soil for the alternative material.

3.4. Linear shrinkage test

It can be postulated that samples with high cassava content appeared to shrink in the outer layer due to water loss but at the same time expanding from within due to cassava fermentation. Swelling was a result of gases produced form the inner part of the brick that was drying slowly. These results stopped at 6% of cassava flour due to development of cracks in the samples when the percentage of cassava was increased. And since the highest compressive strength was achieved at 1.5% of cassava flour, samples from the same are considered for linear shrinkage and compared to termite mound bricks as shown in Fig. 4.

Results show that there is lower shrinkage rate in the alternative material with 1.5% cassava flour compared to termite mound bricks. This phenomenon is probably caused by the cassava polymer forming a film around the soil particles where the large amylopectin molecules [18] formed from splitting of cassava starch avoid evaporation by blocking surface pores.

3.5. Abrasion test

The results show that the control sample with 0% cassava flour is the least resistant and one with 6% cassava flour is the most resistant to abrasive forces. In comparison to the mound brick, samples with 1.5% cassava flour lost about 50% of its material. The 6% cassava flour samples performed better in resisting wearing by soil friction than the bricks from the termite mound soil. The comparison between various secondary bricks for the studied amount of cassava flour in the mix shows that the samples with 6% cassava flour are the best against abrasion. Ranked next in superiority against abrasion are the 1.5% cassava paste specimens (Fig. 5).

3.6. Water absorption test

The test was conducted to ascertain the behavior of the secondary material, when one surface is exposed to water for about an hour. It was found that the 1.5% and 6% cassava flour samples performed better and showed similar trend. The rate of water absorption is highest for samples containing 3% of cassava flour. The reference specimens and the bricks from the termite mound showed a complex

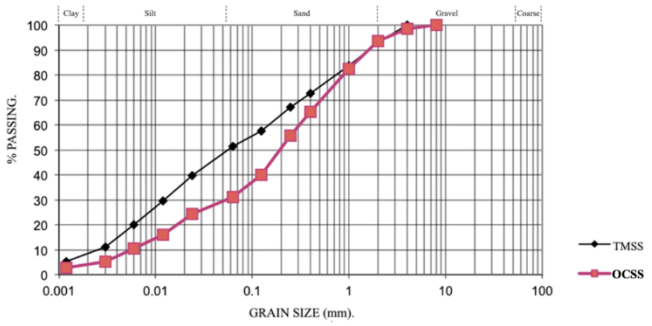


Fig. 2. Soil classification graph.

Table 3
Results for compressive strength of natural termite mound cubes.

Sample	Area (mm^2)	Weight (kg)	Crushing load (kN)	Compressive strength (N/mm^2)
1	3300	0.319	2.6	0.788
2	3300	0.316	2.4	0.727
3	3300	0.317	2.1	0.665
Average				0.76

Table 4
Results for compressive strength of termite mound bricks.

Sample	Area (mm^2)	Weight (kg)	Crushing load (kN)	Compressive strength (MPa)
1	4225	0.517	10.2	2.414
2	4225	0.602	17.2	4.071
3	4900	0.506	11.2	2.286
Average				2.92

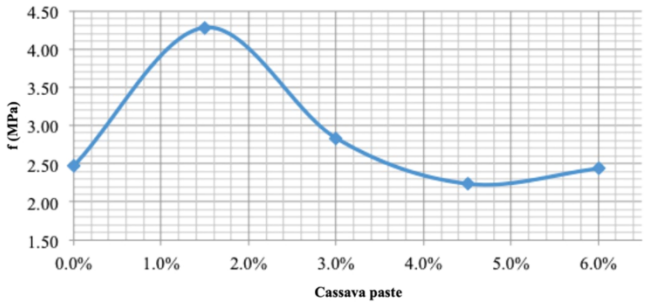


Fig. 3. Compressive strength to percentage of cassava paste.

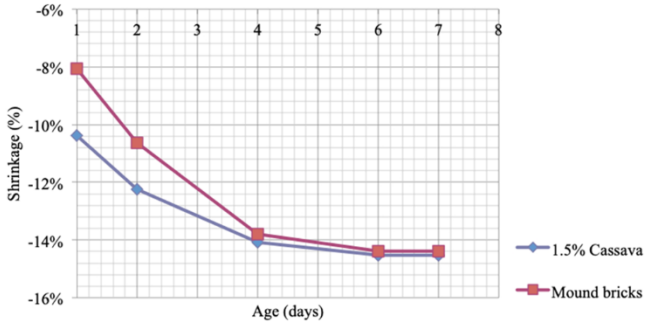


Fig. 4. Comparison of linear shrinkage between termite mound brick and secondary brick.

behavior. The material disintegrates as they absorb water. It was therefore not possible to establish the actual water absorption behavior for such brick samples. Results of water absorption for bricks containing 1.5% cassava flour are shown on Fig. 6 below.

4. Conclusion and recommendation

In general, results from the experimental tests conclude that the compressive strength of the natural termite mound blocks is highly determined by the termites' action of combining saliva, simple sugars and soil. The mimicry process shows positive results where alternative bricks with 1.5% of cassava flour by weight of soil, attained the highest strength at 4.28 MPa better than that at 0% and higher than that of some kiln fired clay bricks. This may be attributed to the increased binding property from the introduction of

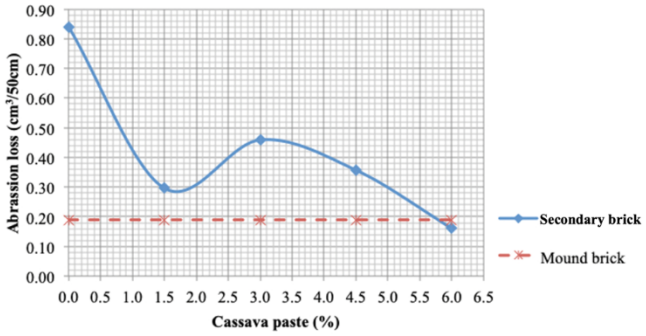


Fig. 5. Abrasion test results of the termite mound brick and the secondary brick.

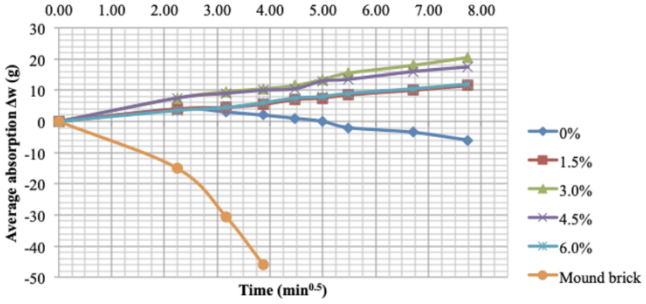


Fig. 6. Average initial rate of water absorption.

cassava paste.

From the findings, the study has shown the potential of using locally available material to increase the strength of clay bricks. This may serve as an opportunity, especially in rural and peri-urban areas, to source all construction materials locally, bringing a more sustainable approach.

This study recommends further experiments that will include methods to separate silt and clay to proportionally be added in the mimicry procedures. Also, further exploration and comparison need to be done on the materials for biomimicry by using industrial polysaccharides and cellulase instead of cassava and other starch based organic matter. Moreover, from the tests performed, it was concluded that with an addition of 1.5% cassava flour by weight of soil, the brick attained the highest compressive strength but nothing has been studied to show what happens between 0–1.5% and 1.5–3%.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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