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RESEARCH PAPER

SUSTAINABLE CERAMIC HIVE FOR BEEKEEPING IN WEST AFRICA: STRUCTURAL DESIGN AND MATERIALS ASPECTS FOR MASS PRODUCTION

L. Gbologah[1], **Y. Hou**[2]*, **E. Gaveh**[3], **D. M. Dela**[1] and **P. S. Kwawukume**[1]
[1]*College of Art and Built Environment, KNUST, Kumasi*
[2]*College of Engineering, KNUST, Kumasi*
[3]*College of Agriculture and Natural Resources, KNUST, Kumasi*
**Corresponding author: lgbologah.cass@knust.edu.gh; yhgbologah.coe@knust.edu.gh*

ABSTRACT

Most hives used for traditional beekeeping in West Africa (tropical zone) are made of wooden materials, which are light in weight, movable, and relatively available. The traditional beehives are less technical to construct and managed by end-users, but normally suffer from natural ageing, and termite and rodent attack. The wood used in construction also causes deforestation further leading to climate challenges. Though plastic hives were introduced in modern beekeeping, the cost and ageing problems are still challenges for end-users in tropical countries. This paper aims to fabricate ceramic beehives with dimensional and thermal stability with a longer lifespan from local materials for sustainable beekeeping activity in West Africa. The ceramic hive is designed to have a common structure of removable combs with top bars; porous ceramic interlocking slabs and embedded in metallic frame to form a rectangular shape. The slabs were of insulating properties, specially developed from Mfensi (MF) and Teleku Bokazo (TB) kaolin clays, obtained from Ashanti and Western regions respectively. X-ray fluorescence was used to determine the chemical compositions of raw materials used. Phases of the fired products were characterized by X-ray diffraction. Wet to fired linear shrinkages, apparent porosity and water absorption of the products were also measured. Among all specimens, the one with the lowest fired linear shrinkage of 8.9%, providing dimensional stability, and highest water absorption of 34.7%, leading to insulating performance, was used for hive body fabrication. Under the expectation, during the field test, the selected components of the fabricated ceramic hive lowered the temperature in hot weather, and also stabilized the inner temperature even when the ambient temperature was low. Moreover, the hive was successfully colonized rather than the wooden hive in use, and yielded honey even at the lean season.

Keywords: *Ceramic hive, beekeeping, design, sustainable, honey*

INTRODUCTION

Honey bees can deliver multiple benefits worldwide; enhance pollination of crops, influence or yield food production, increase growth of flora and flowering trees, which lead to increased absorption of carbon dioxide (CO_2) and other harmful emissions, and oxygen (O_2) production. Due to the significant potential–merits of the honey bee, its beekeeping technology will make sure a healthy, safe and productive space, which is commonly known as the beehive, to house the bees (Crane, 1999).

Natural hives chosen by bees can be any cavity, hollow log or tree, rock cavity, or a discarded container. The hive used by beekeepers varies with the level of modernization and location (Crane, 1999). In tropical countries, artificial hives used by indigenous beekeepers were woven straw (skep) and palms, baskets, calabash, thatched hives, clay pots or masonry, which they hung on trees, but sometimes did not last for more than one season, and more often were blown off by wind (Irvine, 1957). Modernization has brought in new ideas, the commonly used hives in tropics are fixed comb hive, and removable comb hives with top bars or frames (Smith, 1953; Тесля, 2006). New designs were also introduced with specific change for temperature insulation (Benincasa and Buckman, 2013; Liang, 2013), pet control (Huang, 2013; Richardson, 2018), feeding system (Gerogiannis, 2017; Xu, Yang, Wang and Chen, 2009), and air or sanitary ventilation (Тесля, 2006, 2018), etc.

In tropical beekeeping regions, high temperature and low humidity (about 16%) enable the bees to ripen the honey rapidly. High water content from poor hive results in fermentation and loss of freshness. Yeast in the honey may cause fermentation during storage leading to high acidity. Honey water content of up to 20% or more is not desirable (Singh and Singh, 2018; Umesh Hebbar, Rastogi, and Subramanian, 2008). However, high moisture content during the raining season results in high water content in honey which has to wait until the dry season for harvesting. Moreover, temperature for a colony to develop is around 32-35 ^{o}C; when the temperature is high (higher than 35 ^{o}C) in the hive, bees spend lots of time and energy in cooling down the environment by organized fanning of wings, otherwise, the brood will die and the honey will get dehydrated too quickly (Southwick and Heldmaier, 1987). Besides, the high temperature in the hive also leads to poor honey quality (Turhan *et al.*, 2008). Therefore, the hive had to be protected from the full mid-day heat and early afternoon sun. Overheating of the hive also leads to absconding of the bees. Apart from that the bees also require constant water supply for hive cooling, or tend to consume the honey instead (Smith, 1953). When the temperature is low (lower than 35 ^{o}C), bees cluster over the brood to warm brood (Southwick and Heldmaier, 1987).

Worldwide, the design and materials adopted for hive construction include wooden materials (e.g. lumber blocks as used by Wood (1916) to make economically strong and weatherproof hive), ceramic (modern beekeepers use discs of slate leaned up against the mouth of ceramic hives made of clay/mud in Crete (Francis, 2012), metal (e.g. metal wall with inner ply board liner (Hageman, 1950), emphasize on ventilation, inflammable feature and artificial feeding), plastic (e.g. plastic foam was used by Platt (1983) for heat insulation for the tropical environment; and Glasscock and Pearson (1980) for protection from vermin), layers of polystyrene foam/grass/fabrics for insulation in cold weather (Liang, 2013), and both wood, for best health and behaviour of bees, and plastic materials for handles all around (William, 1963). For large-scale hive, Orletsky *et al.* (1998), Huang (2013), and Mullins (2014) invented a structure designed for housing a plurality of bee colonies. Though ceramic material was recorded as one of the very early options for beekeeping (Crane, 1999; Francis, 2012; Taxel, 2006), it is gradually fading out of sight. To meet Sustainable Development Goals (SDG) published by United Nations, materials that are locally available, affordable, and sustainable should be considered. Besides, a sustainable beehive product has to be relooked at, especially in West Africa - tropical zone.

In Sub Saharan Africa (West Africa), weather patterns have annual sunshine of more than 2800 h, an average temperature of 18~40 ^{o}C, and a mean annual rainfall of 700~1600 mm. In such an environment, particularly in West Africa which comprises mainly of developing countries with agriculture as the main activity, developing an economic, strong, weatherproof, thermally stable, and durable hive for beekeeping in the region becomes more urgent and important.

This paper aims at developing ceramic beehives with dimensional and thermal stability, and longer lifespan from local materials for sustainable beekeeping activity in West Africa. This is to meet the criteria of the world's sustainable development (Assembly, 2015; Davidson *et al*., 2010; Zimmerman and Anastas, 2003). The structural design of the hive is targeting easy assembly, suitability for mass production, and less technical in installation.

EXPERIMENTAL PROCEDURE

Formulation of insulating slabs

Mfensi (MF) and Teleku Bokazo (TB) kaolin clays obtained from Ashanti and Western regions of Ghana respectively were used. The clays were beneficiated by crushing and pulverising.

The classical preparation is as follows: the beneficiated Mfensi (MF) and Teleku Bokazo (TB) kaolin clays were initially mixed with sawdust in predetermined proportions, and then later mixed with water to form nodules, which was air-dried for 48 h and fired to 1180 °C at a heating rate of 100 °C per hour to form grog (fired clay). The formed grog was further crushed by jaw crusher (FS 4901, Stoke-on-Trent) and gyratory crusher (14130, England), and further sieve graded into fine (< 1.7 mm) and coarse particles (1.7-3.35 mm) for body formulation of the insulating slabs. The fine and coarse grog used were weighed separately according to body formulation design, as shown in Table 1. Another batch of MF clay and TB kaolin were crushed and pulverized (14218, England), and then mixed with grog for mould pressing to obtain the designed shape. The body formulation was designed to take a constant percentage proportion of plastic binder (MF clay) with increased grog content, which was expected to improve upon the dimensional stability and porosity of the slab. The pressed slabs were later air-dried for 48 h, fired to 1050 °C at a heating rate of 50 °C per hour and cooled, and then used for the assemblage of the beehive. The formulation scheme of slabs for the beehive is shown in Fig. 1.

Characterizations

The chemical compositions of the clay minerals were determined by X-ray fluorescence (XRF; SPECTRO X-LAB 2000, Germany). Phase identification was performed using X-ray diffraction (XRD), D/MAX-RA model XRD machine with CuKα radiation. The physical characterizations: plasticity index, dried and fired linear shrinkages, apparent porosity and water absorption on formulated bodies were tested.

Plasticity index

The plasticity index was determined by Atterberg Limits (Plastic Limits (PL), Liquid Limits (LL) and Plasticity Indexes (PI)) according to the ASTM standard-D4318. 200-g of the MF clay was weighed and appropriately mixed with distilled water to a subjective plasticity.

Table 1: Batch formulation details

Samples	% wt.		
	MF Clay	**TB Kaolin**	**Grog**
A	33.3	41.7	25.0
B	33.3	37.7	29.0
C	33.3	33.3	33.3
D	33.3	27.7	39.0
E	33.3	20.0	46.7

Coarse: Fine ratio of grog particles for body formulation = 55:45 (Chesti, 1986)

Grog (Composition): MF clay (20~55%), TB Kaolin (5~30%), Sawdust (40%)

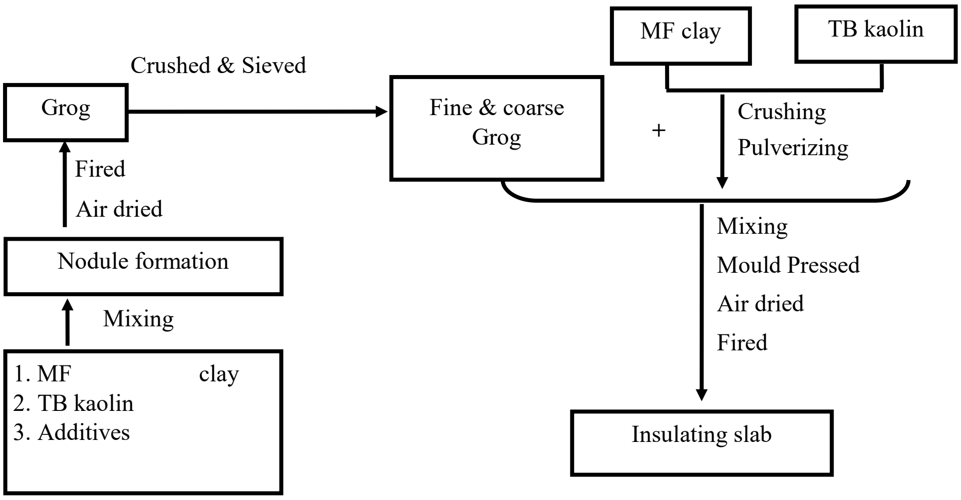


Fig. 1: Illustrative scheme of formulating slabs for beehive fabrication

The cup of the liquid limit apparatus was filled and a standard cone was released to penetrate the clay. Measurements of the penetrations were taken and accordingly recorded in Atterberg limits Data Work Sheet. The liquid limit (LL) is the water content at 20 mm penetration of the standard cone into the clay. The clay in the plastic state was rolled into a thread with 3 mm thickness and weighed. The sample was oven dried at 110 °C for 24-h and re-weighed. The plastic limit is the minimum water content at which the clay was rolled into a thread 3 mm thick. Plasticity Index (PI) is the range of water content over which the clay remains in the plastic condition. It is the difference between the liquid limit and the plastic limit: $PI = LL - PL$.

Shrinkage measurement and calculation

This was carried out under ASTM C 326-03 (ASTM, 2006) protocol. Representative samples of the materials were uniaxially die-pressed in steel moulds of dimensions (55 mm x 55 mm x 55 mm). The plastic-formed test specimens were suitably identified and marked with shrinkage reference lines 50 mm apart on the specimens. Marking was done as soon as the specimens could be handled without distortion. The marked specimens were then placed on a lightly oiled pallet and allowed to dry at 20 ~ 40 °C for 24 h. During this preliminary drying period, the specimens were turned 90° several times (>4) at 2-h intervals to eliminate possible warping. After the initial drying period, the specimens were then placed in a drying oven at 110 ° C and further dried for 24 h. The distance between shrinkage reference marks on dried or fired specimens was measured to the closest (0.1 mm) with callipers of suitable accuracy. The linear drying shrinkage as a percentage of plastic length was calculated as shown in the equation 1 (ASTM, 2006).

$$S_d = \frac{L_p - L_d}{L_p} \times 100\% \qquad (1)$$

where S_d is linear drying shrinkage, %; L_p is plastic length of test sample; L_d is the dry length of test specimen. The total linear shrinkage after drying and firing of the specimens was calculated as a percentage of plastic length, as shown in equation 2 (ASTM, 2006).

$$S_t = \frac{L_p - L_f}{L_p} \times 100\% \qquad (2)$$

where S_t is total linear shrinkage after drying and firing, %; L_p is plastic length of test sample; L_f is fired length of test specimen.

Water absorption

This was performed on the sintered specimens by boiling water method following the ASTM C 20-00 protocol (ASTM, 2005). The sintered specimens were air-dried in an oven to a constant weight by heating to 110 °C to determine the dry weight, D, in grams to the nearest 0.1 g. The specimens were then placed in water and boiled for 2 h. During this boiling period, the entire specimens were covered with water at all times and allowed no contact with the heated bottom of the container. After the boiling period, the specimens were allowed to cool to room temperature while still completely covered with water. The specimens were allowed to soak in water for 12 h after which the suspended weight, S, while suspended in water was determined by suspending the specimen in a loop of AWG Gage 22 (0.643 mm) copper wire hanged from one arm of the balance. The saturated weight, W, was determined after suspended weight by blotting each specimen lightly with a moistened smooth linen to remove all drops of water from the surface weighed in air to the nearest 0.1 g.

Water absorption, A, expressed as a % relationship of the weight of water absorbed to the weight of the dry specimen was calculated as shown in equation 3 (ASTM, 2005).

$$A = \frac{W - D}{D} \times 100\% \tag{3}$$

Study site

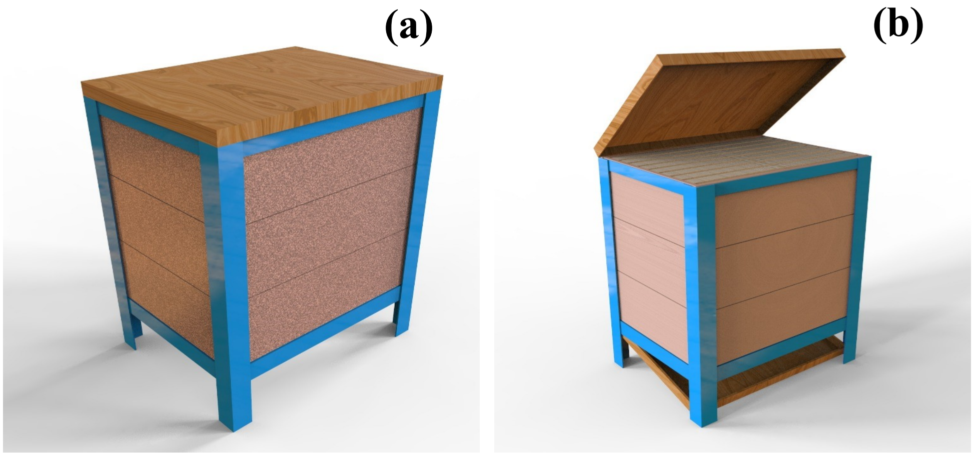
This research work was carried out at the Research Farm (located at Anwomaso) of Kwame Nkrumah University of Science and Technology, Kumasi, Ghana. The farm had a dense vegetation of palm trees, fruit trees and vegetables. A complex blend of species surrounded the experimental hives.

Hive design

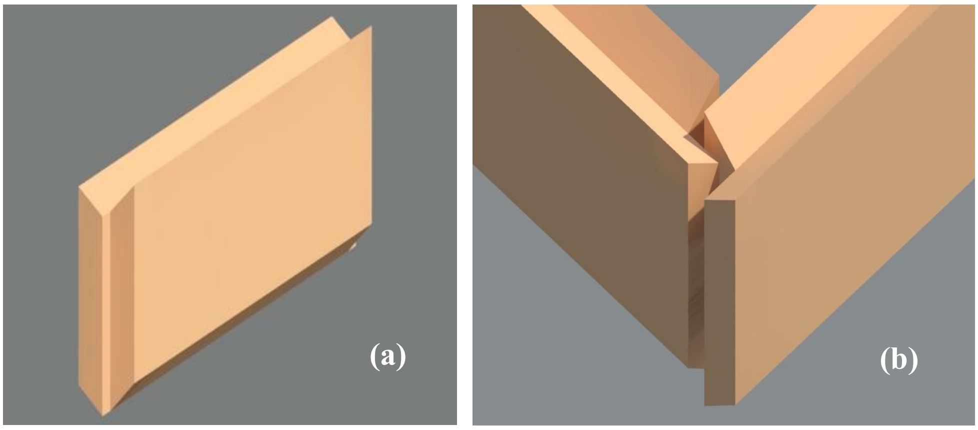
The structural design of the beehive in this paper was inspired by the traditional and modern wooden beehives. The ceramic hive developed in this study is a type of removable comb hive with top bars, which is also the most common and efficient type of hive used in the Northern region of Ghana (Abdul-Malik and Mohammed, 2012). The prime concern of the hive is its easy assembly, the hive was composed of interlocking insulated slabs, housed in a metallic frame. The top cover of the hive was made of wooden material for easy operation. To avoid insect attack and rainfall disturbance, the hive was raised from the floor by adding legs to the metallic frame. The outer design is shown in Fig. 2a.

In this paper, a prototype beehive was built. Inner space of the hive chamber is divided into two sections: the workers (bees)' chamber and the queen's chamber, with the former measuring 381.0 mm (W) × 279.4 mm (H) × 228.6 mm (L), while the latter measured 381.0 mm × 279.4 mm × 76.2 mm. The division of chamber is aimed at preventing easy movement of the queen to workers' chamber leading to contamination of the honey with its excreta. This is achieved by using a welded wire mesh with a smaller size for the queen's chamber. Five wooden frames of measurement of 393.7 mm × 203.2 mm × 25.4 mm were used with the mesh embedded in. After fixing the colony frames, the chamber is covered with slabs of 20.3 mm intervals, before the cover to enable a stable thermal atmosphere against hot and cold weather, as well as heavy rainfall and animal attack. The interval arrangement of slab on the top of the chambers considered the easy movement of bees in the upper space. The design of the cover took into consideration the easy heating up of the chambers in cold weather. So a piece of aluminium sheet was chosen to bind together with plywood (20.3 mm thickness) serves as cover. The entrance of the hive was kept at the lower side of the workers' chamber, created by triangle incision in the slab, with a total quantity of nine distributed evenly and horizontally.

The bottom was covered with a piece of plywood first, and followed with a piece of slab covering the entire bottom to avoid attack from termites. The bottom was latched to opposite sides of the metallic frame. The chamber design is shown in Fig. 2b.



Figs. 2: (a) Outer design of beehive (b) Chamber design of beehive with slab arrangement



Figs. 3. (a) 3D display of slab design, (b) 3D display of slab interlocking

The size of slabs was 431.8 mm × 330.2 mm × 25.4 mm. Rhinoceros (3D) software was used to render the 3D mould design for interlocking slabs as shown in fig. 3. The joint of the slab was of landed scarf tongue and groove shape. Fig. 3a shows a 3D display of slab design and Fig. 3b shows a 3D display of slab interlocking.

Hive construction

The welded metallic frame was constructed from angle bars of 38.1 mm into 431.8 mm (Length) by 330.2 mm (Width) by 558.8 mm (Height) dimensions. The hive body was 254.0 mm above the floor. Slabs were slid into the metallic frame to form the two chambers. After inserting the wooden frames for the colony, the slabs were then arranged on the top of the hive, and followed by the wooden cover.

Duration

Both wooden and ceramic hives of the same type of structural design were installed on the same day. The hives were then left for six months un-attended to without a bait to observe the durability. In the subsequent three months after the durability observation, activities of honey bees appeared only in the ceramic hive and were closely monitored.

RESULTS AND DISCUSSIONS

Chemical and physical characterizations

Chemical analysis of the clays used are presented in Table 2. MF clay which was plastic in nature provided mechanical strength and had a higher total flux content (Na_2O, K_2O, MgO, CaO, and MnO) of 5.61% compared to that of TB kaolin clay of 1.21%. TB kaolin clay had a relatively high refractory oxide (Al_2O_3) content of 20.40% as against MF clay 13.82%. The presence of fluxing oxides induced SiO_2 to melt at reduced temperatures required for sintering (Ibrahim, Naga, Kader, & Salam, 1995). The plasticity index of MF clay was measured and obtained by the ASTM standard-D4318. The plasticity index of MF clay had a value of 22.54 (higher than 17), indicating a high plasticity, which is in tandem with the loss on ignition (L.O.I) value of 10.0% shown in Table 2 also in line with the high plasticity of bond clays (Worrall, 1982).

XRD patterns of fired grog and insulating slabs are shown in Fig. 4. From the XRD spectra, mullite (PDF 15-0776) was observed to have been developed in the grog, which increased the bulk density of fired specimens and reduced volumetric change over temperature variation (Ibrahim et al., 1995), leading to stable dimensions. With the addition of grog into body formulation of slab, minor mullite peaks were observed in the slab. Apart from that quartz (PDF 46-1045) is also present in both grog and slab, due to ratio of alumina to silica exist in MF clay and TB kaolin used; excess silica present in the form of quartz after firing.

Fig. 5 shows the percentage linear shrinkage and water absorption results of the fired specimen with a varied percentage proportion of the grog. It was observed that the linear shrinkage of the fired specimen was in the range of 8.9 to 11.0% with grog percentage variation from 25.0 to 46.7%. More grog addition resulted in lower percentage linear shrinkage and further lead to higher dimensional stability during slab production. The lower linear shrinkage might be due to the stabilized phases of materials in the grog at high temperature and less contribution from burning off of organic matters in raw

Table 2: Chemical analysis of clays used in slab formulation

Oxide Composition	% Wt.	
	MF Clay	TB Kaolin
Al_2O_3	13.82	20.40
SiO_2	65.26	70.60
Na_2O	2.06	0.26
K_2O	1.66	0.76
MgO	1.28	0.06
Fe_2O_3	1.90	0.96
CaO	0.54	0.13
TiO_2	0.04	0.12
MnO	0.07	-
Loss on ignition	10.0	6.74

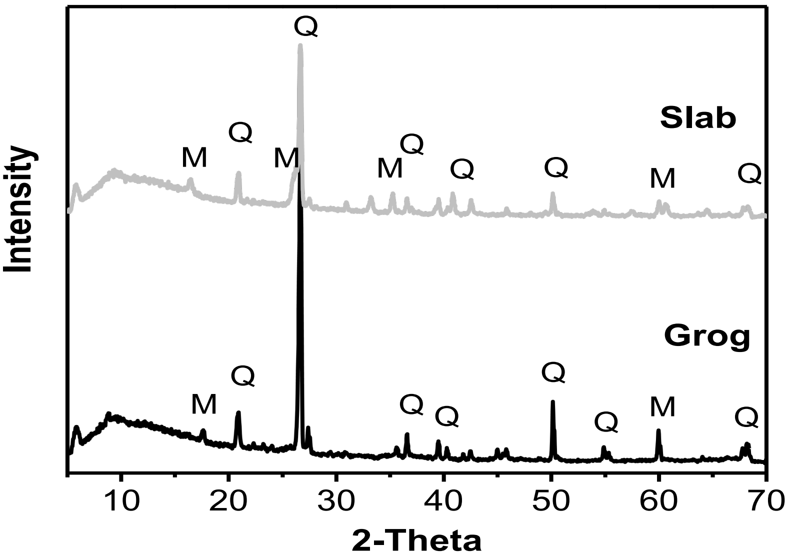


Fig. 4: XRD patterns of fired grog and insulating slab, Q-quartz, M-mullite

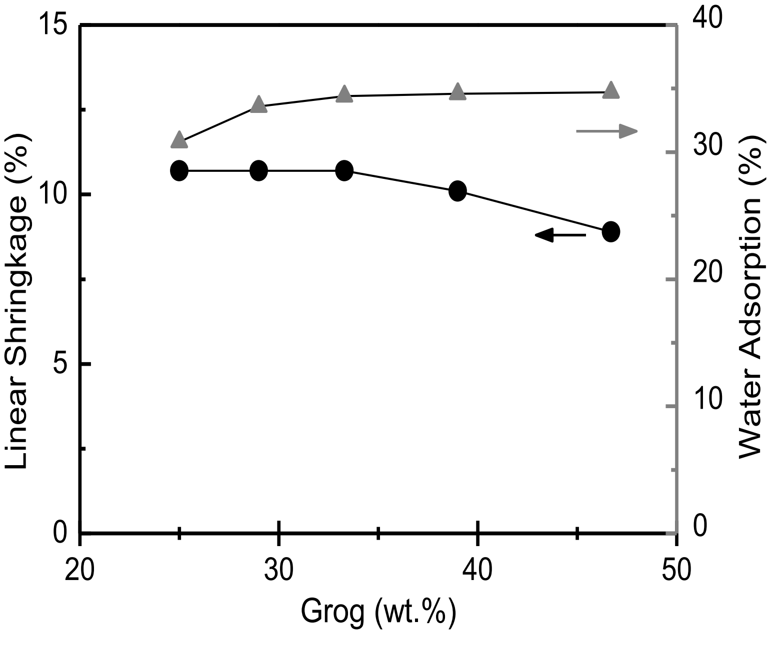


Fig. 5: Percentage linear shrinkage and water absorption results of fired specimen

clay materials, hence lower volume change occurring during the second firing in slab formation.

However, more of the grog addition resulted in higher water absorption percentage, which is of 30.8~34.7%. The higher water adsorption percentage meant higher pore density, hence, better insulating property leading to a thermally stable space in the hive. The higher water absorption percentage might be due to the porous nature of the grog, which was as a result of the presence of a combustible material-sawdust used for grog formation. Therefore, a higher percentage of grog addition is beneficial to the targeted performances (stable dimension and better insulation) of slab fabrication.

In the body formulation design, composition with the lowest linear shrinkage 8.9%, and highest water absorption 34.7% which are responsible for dimensional stability and insulating performance, respectively, was selected for slab production.

Installation and accessibility

The constructed ceramic and wooden hives were installed firmly on a levelled floor and about ten meters apart. The area around the mounted hives was cleared of weeds to safeguard the bees during a bush fire, especially in the dry hot weather.

Colony development and honey yield

After six months of durability test, the developed ceramic hive showed no visible sign of deterioration as compared to the traditional wooden hive which showed some level of decay (wood rot).

In the subsequent three months, a trace of activities of bees in the installed ceramic hive was observed. The temperatures inside, t_{in}, and outside, t_{out}, the hive was monitored by a thermometer in one of the days, and proved good thermal stability of the atmosphere inside the hive for both honey production and brood growth; (Fig. 6) in the first two hours, t_{out} was 38 °C and t_{in} was 32 °C, in the next two hours, t_{out} drop to

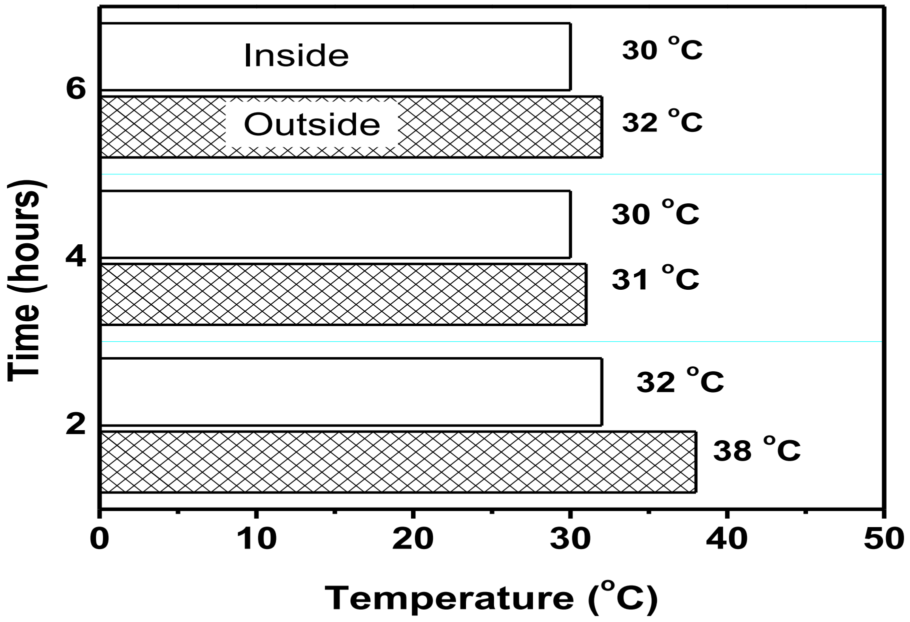


Fig. 6: Temperature detected inside and outside the developed ceramic hive

31 ^{o}C but t_{in} was 30 ^{o}C, in the third two hours, t_{out} was 32 ^{o}C but t_{in} still maintained at 30 ^{o}C. Inferring that the insulating slab controlled the temperature rise in hot weather, and stabilized the temperature even when the ambient (outside) temperature dropped. Moreover, the detected temperature inside the hive which did not exceed 32 ^{o}C also created an enabling environment for colony development and quality honey production. High ambient temperatures (above 35 °C) associated with traditional hives, could lead to high acidity and over 100 mg/kg in hydroxymethylfurfural (HMF) (Da Silva, Gauche, Gonzaga, Costa and Fett, 2016; Turhan *et al.,* 2008), which is a break-down product of fructose in honey. The amount of HMF present in honey is therefore used as a guide for storage length and the amount of heating that has taken place. Good honey requires below 10 or 15 mg/kg of HMF to enable further processing and then give some shelf life before a level of 40 mg/kg is reached (Fallico, Arena and Zappala, 2009).

The honey was harvested in the night during the dry season (January). During the harvest, after removing the cover, the slabs laid on the top of the frames were tightly bonded by bee wax, which was done by the bees. The wax sealed-top by the bees could be as a result of moisture retention and heat loss prevention in the hive during the dry season. To observe the situation inside the chamber, the authors had to break the slabs on the top. Inside the chambers, the joint areas of ceramic slabs as hive body as well were sealed by bee wax. Bee colony was formed with a certain thickness on each frame. The honey yield from the ceramic hive was about 500 mL over five frames in the space of 381.0 mm by 279.4 mm by 279.4 mm in lean season. The colonized hive during harvesting the honey is displayed in Fig. 7.

CONCLUSION

To develop ceramic beehives with dimensional and thermal stability, and longer lifespan from local materials for sustainable beekeeping activity in West Africa, a ceramic hive of removable comb with top bars was designed and fabricated by making insulating interlocked slabs from fired local clays. The ceramic body with a lower linear fired shrinkage of 8.9% and the highest water absorption of 34.7% was used for hive body fabrication. The lowest linear shrinkage of the slab material provided dimensional stability and the higher water adsorption percentage leading to better insulating protective performance. Though insulating properties can ease the temperature rise, it can also ease the temperature drop, out of which the ceramic slab

Fig. 7: Colonized hive during harvesting of honey

guarded environment was supposed to maintain the inner hive temperature space to exhibit a thermally stable nature. After six months of durability test, the hive made of wood showed natural deterioration and even developed cracks. In the subsequent three months, bees migrated into the ceramic hive and settled rather than the wooden hive in use, and yield honey even at the lean season. The structural design (metallic frame + ceramic body) of the ceramic hive prevented rodent attack.

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