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ORIGINAL RESEARCH ARTICLE

THERMAL AND MECHANICAL PROPERTIES OF CLAY AND DROP-OFF OF CEIBA PENTANDRA (KAPOK) PLANT WOOL MIXTURE

A. T. Abdulrahim[1*], S. Abdulkareem[2], S. A. Abdulraheem[1] and W. J. Mohammed[1]

[1]*Department of Mechanical Engineering, University of Maiduguri, P.M.B. 1069 Maiduguri, Nigeria*
[2]*Department of Mechanical Engineering, University of Ilorin, P.M.B. 1515, Ilorin, Nigeria*

**Corresponding author's email address: engrabdulrahimat@gmail.com, abdulrahimat@unimaid.edu.ng*

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ABSTRACT

This study is aimed at the investigation of the effects of the addition of clay to drop-off of Ceiba pentandra (Kapok) plant wool on the thermal and mechanical properties of the materials produced. Because of the considerable increase in the use of insulations in many heat devices, process and systems, and dependence on imported insulations, the need to process natural fibre insulations to form rigid or semi-rigid material using appropriate and sustainable binding material cannot be over emphasized. For this study, Kapok wool and clay mixture were investigated. Five samples were prepared: Sample A was 100% Kapok wool while samples B, C, D, and E were mixture of Kapok wool and Clay in water with varying percentage of clay quantities (Kapok to Clay ratio; B 2:1, C 2:1.5, D 2:2.5, E 2:3.5). The samples were prepared into cylindrical shapes, compressed and dried. The Thermal conductivity meter on Armfield Heat transfer equipment was used to find the thermal conductivity of each sample, while the thermal diffusivity and thermal resistivity of samples were determined using appropriate formula. Universal Testing Machine (Model: FS 50AT) was used to determine the stress at Yield and Young Modulus of elasticity for samples B, C, D, and E. Results show that the density of sample increases with increase in clay content. Thermal conductivities of the samples after the addition of clay ranges between 0.027 (W/mK) and 0.013 (W/mK). Reversed was the case for Thermal Resistivity, the value of thermal resistivity first decreases with addition of clay content (sample B) and then started increasing with increased clay content in the samples, and the values range from 37.037 to 76.923mKW^{-1}. Thermal diffusivity of sample decreases from 1.2762 x10^{-3} m^2/s to 0.2810 x10^{-3} m^2/s with increasing clay content. Results also show that the Stress at Yield of samples range from 0.012 N/mm^2 to 0.022 N/mm^2 while the Young Modulus of elasticity range from 0.113 N/mm^2 to 0.222 N/mm^2. Kapok wool – Clay combination of ratio 2:3.5 (Sample E) have the highest value of thermal resistivity and lowest thermal diffusivity, though with high density, which suggests it to be the best among samples in the study for insulation purposes. The products are recommended for use as insulations of thermal storage for medium temperature applications.

1.0 Introduction

Thermal insulations play a major role in the design and production of energy efficient process, devices and systems because of their ability to retard heat transfer by acting as barriers in the path of heat flow. The variety of insulation materials available are mostly those that are primarily made of fiberglass, mineral wool, polyethylene, form, or calcium silicate (Cengel, 2007; Holman, 2010). It is important to note that synthetic fiber composites are being replaced by environmentally friendly materials such as natural fiber because of their low weight, density, cost, renewable nature among others (Ayugi, 2011). Natural fiber low to zero toxin ratings, easy to reuse and dispose with significant health benefits have also been recognized as additional advantages (Andy et al., 2011).

Drop-off of Ceiba pentandra plant (Kapok) wool have been reported in literature as a material for thermal insulation. Studies carried out by Abdulkareem et al. (2016) and Abdulkareem et al.

(2015a,b) on the investigation of thermal insulation properties of Biomass composites involving Kapok wool, Sugarcane bagasse, Coconut fibre, Luffa Cylinderica and Cellulose using Molasses as binder revealed the potentials of composites from these biomass materials as insulation materials because of their high thermal resistivity and low thermal conductivity. Ali and Zeitoun (2012) have also investigated Apple of Sodom Fibre (Calotropis procera) as insulation material, and its potential as a good insulator has been established.

Because of the considerable increase in the use of insulations in many heat devices, process and systems, there is growing needs for the development of new and more effective as well as affordable insulation materials. The need for the use of locally available materials that will eliminate the problem of importation of insulators from other countries cannot be over emphasized. Natural fibre insulations can be process to form rigid or semi-rigid rolls or loose insulation material for a variety of uses. Clay could be a binding agent for processing natural fibre into a rigid or semi-rigid insulation materials because of its fine particle size and plastic nature as well as its refractory tendencies (Lewis, 2013; Ashby and Jones, 1998). Studies have shown the availability of clay in Nigeria as well as its uses for pottery, mud building of local houses, refractories and glaze making (Adams et al., 2018; Adams et al., 2017; Counts et al., 2000). To this effect, this study is aimed at the investigation of the effects of the addition of clay to drop-off of Ceiba pentandra (Kapok) plant wool on the thermal and mechanical properties of the insulation materials produced.

2 Materials and Methods

2.1 Samples preparation

The locally available insulating materials that have been considered in this study are Kapok wool and clay. Kapok pods were obtained at the University of Maiduguri, Maiduguri, Nigeria from Kapok Trees. The Kapok wool was removed from its pod (Figure 1a) and hand picking of the kapok seed in the Kapok wool was done and it was then brushed to remove other unwanted particles (Figure 1b). The Kapok wool comprise 64% cellulose, 13% lignin and 23% pentosane (Kobayashi et al., 1977).

Figure 1: Kapok Wool Source and Processing: (a) Kapok Pod; (b) Kapok Wool, Seed, Exocarp and other unwanted particles

Clay was collected from a deposit in Maiduguri, Nigeria which was further dried and finally crushed down to smaller sizes. The clay was sieved by hand through a 500 µm sieve to remove coarse particles and foreign materials that might have been present in the clay. The chemical compositions of clay sample were determine using Single beam spectrophotometer (with test kits, hot plate and furnace) at the Department of Geology, University of Maiduguri, Maiduguri, Nigeria.

Samples were weighed using an Electronic Kitchen Scale Model: SF 400. Five samples of the materials were prepared. Sample A is 100% Kapok wool while samples B, C, D, and E are mixture of Kapok wool with Clay mixed in water with varying percentage of clay quantities as shown in Table 1. The samples were prepared into cylindrical shapes of thickness (t) in m and diameter (d) in m. The volume (V) is given by equation 1:

$$V = \pi R^2 t \qquad (1)$$

where: $R = d/2$

Table 2: Composition of samples by mass

S/No.	Sample	Kapok (g)	Clay (g)	Water (ml)
1.	A	20	-	200
2.	B	20	10	200
3.	C	20	15	200
4.	D	20	25	200
5.	E	20	35	200

A 110mm diameter mould was used to mould the samples. Sample A was achieved by adding 200ml of water to the 20g of Kapok wool and vigorously mixing the contents until the Kapok wool was soaked in the water. For samples B, C, D and E, 200ml of water was mixed with the corresponding mass of clay for each of the samples and them mixed with the Kapok wool. The mixture was poured into the mould and compressed by a total load of 196 N. The samples were left for one day in the mould, then removed and sun dried for 2 days. The samples were oven dried for 9 hours at 105 °C before tests were carried out. This was done to eliminate moisture content if present in the samples. A total number of 5 samples were produced. The samples are as shown in Figure 2.

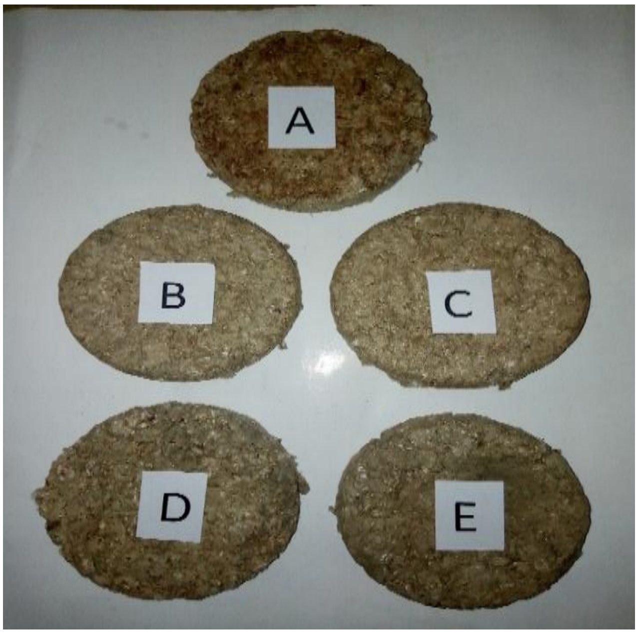

Figure 2: Dried Samples of A, B, C, D, and E

Determination Density of sample

The density of the sample was obtained from Equation 2 according to Abbott (1980):

$$Density = \frac{Mass}{Volume} \qquad (2)$$

Thermal conductivity

The Thermal conductivity meter on Armfield equipment (Model: HT12) with Heat transfer service unit (Model: HT10XC) equipment were used to check the thermal conductivity of the materials. The probe consists of single heater wire and thermocouple. When constant electric power (energy) is given to the heater, the temperature of the wire will rise in exponential progression. Temperature rising with time axis scaled in logarithm. The angle of this line increases if the sample has less thermal conductivity (TC) and decreases if it has higher TC.

Corresponding author's e-mail address: abdulrahimat@unimaid.edu.ng

Therefore, TC of a sample was determined from the angle of the rising temperature graphic line (Armfield equipment model HT12 manual).

Thermal conductivity of sample, k [W/mK] is expressed as given in Equation 3 as reported by Tripathi et al. (2016), Eeday et al. (2014) and Rodriguez et al. (2011):

$$k = \frac{q In\left(\frac{t_2}{t_1}\right)}{4\pi(T_2 - T_1)} \tag{3}$$

where: q is generated heat per unit length of sample/time [W/m]
t_1 and t_2 are measured time length [sec]
T_1 and T_2 are Temperatures at $t_1$and t_2 respectively [K]

Thermal Resistivity

The Thermal Resistivity of samples were calculated from Equation 4 according to Satta and Steve (2008):

$$\text{Thermal Resistivity, } r = \frac{1}{k} \tag{4}$$

Thermal diffusivity

The Thermal diffusivity of samples were calculated using the expression given by Incropera et al. (2007) as in Equation 5:

$$\alpha = \frac{k}{\ell C_p} \tag{5}$$

where: Thermal Diffusivity, α (m^2/s),
ℓ is the density (kg/m^3) of the material,
C_p is the specific heat capacity (J/gK).

The plot of natural logarithm of change in temperature versus reciprocal of time ($\text{In } \delta T \text{ vs} \frac{1}{t}$) were drawn for the samples, and heat capacity of each sample was obtained from the intercept of the plots.

Compressive Test

The compressive stress test was determined by the use of Universal Testing Machine (Testometric Type: DBBMTCL-5000kg; Serial No. 38140; Model: FS 50AT) at the University of Ilorin, Ilorin, Nigeria for samples B, C, D and E. On sample A, the study of effect of compression stress on the sample was not done since it is 100% Kapok wool. For other samples (B, C, D, E), the samples were mounted one at a time and test speed of 2mm/minute was applied until samples failed after it has reached yield point. The stress at Yield and Young Modulus of elasticity were then recorded.

3 Results and Discussion

Table 2 show the chemical composition of kapok wool

Table 2: Chemical compositions of the kapok wool and clay

Component	Chemical Composition (%)	
	Clay	Kapok wool
Silica (SiO_2)	55.71	-
Alumina (Al_2O_3)	19.86	-
Ferric Oxide (Fe_2O_3)	0.74	-
Titanium oxide (TiO_2)	-	-
Lime (CaO)	7.7	-
Magnesium oxide (MgO)	1.68	-
Potash (K_2O)	7.23	-
Soda (Na_2O)	0.52	-
Manganese oxide (MnO)	1.61	-
Phosphorous pentaoxide (P_2O_5)	1.19	-
LOI	2.8	98.57
Carbon (C)	-	0.99
Hydrogen (H)	-	0.41
Nitrogen (N)	-	0.01

Note: Silica and Alumina were determined by XRF while others by ICP-OES.

Table 3 shows the results of the Density, Thermal conductivity, Thermal Diffusivity and Thermal Resistivity of the samples.

Table 3: Density, Thermal conductivity, Thermal Diffusivity and Thermal Resistivity of Samples of kapok wool-clay mixture

Sample	Density,ρ (g/cm^3)	Thermal Conductivity (W/mK)	Thermal Diffusivity (m^2/s)	Thermal Resistivity (mKW^{-1})
A	0.067	0.0177	1.2762x10-3	56.497
B	0.125	0.027	1.1232 x10-3	37.037
C	0.240	0.026	0.7085 x10-3	38.462
D	0.275	0.021	0.5755 x10-3	47.619
E	0.700	0.013	0.2810 x10-3	76.923

From Table 3, the density of sample increases with increase in clay proportion as reflected in samples B, C, D and E. Sample A has the lowest density while sample E has the highest density. The addition of clay to Kapok wool first caused a rise in thermal conductivity of the sample as shown in Table 4 in the case of sample B, and with increase proportion of clay content, the thermal conductivity decreases as reflected in samples C, D and E. Reversed were the case for Thermal Resistivity: the value of thermal resistivity first decreases with addition of clay content (sample B) and the started increasing with increase in clay content in the sample. This is an indication that Samples C, D, and E have improved insulation properties proportion to increase clay contents.

Table 4 shows the results of the stress at yield and the modulus of Elasticity at failure for the samples.

Table 4: Stress at Yield and Modulus of Elasticity of Samples at Failure

S/No.	Sample	Stress at Yield (N/mm2)	Young Modulus of elasticity (N/mm^2)
1.	A	-	-
2.	B	0.012	0.113
3.	C	0.015	0.148
4.	D	0.020	0.151
5.	E	0.022	0.222

From Table 4, it can be observed that both the stress at yield and the modulus of elasticity increase as the clay content in the sample increased.

The chemical composition of the clay as presented in Table 2 showed significant amounts of SiO_2 and Al_2O_3 (55.71 and 19.86% respectively). The clay can be used as a binder with this level of Silica and Alumina contents, and it is plastic when moist but hard when fired (Lewis, 2013). The results obtained revealed that the value of the thermal conductivities of the samples were found to first increase from 0.0177 W/mK to 0.027 W/mK with Kapok wool to Clay ratio 2:1 while the density increases from 0.067 to 0.125 g/cm^3. The loose fibrous nature of Kapok wool enhances its conductivity and with limited amount of clay added might brought about the increase since clays have plate-like molecules with charges on their surfaces (Ashby and Jones, 1998). More so at the low level the clay may just be serving as a binder and not as a reinforcement. Similar report was made by Ali and Zeitoun (2012) when they asserted that low-density fibers (Calotropis procera) with no resin (loose fibres) have a lower thermal conductivity than the ones made in a board form using Phenol-Formaldehyde resin. The addition of more clay to obtain a Kapok Wool to Clay ratio 2:1.5 brought about a reduction in thermal conductivity to 0.026 W/mK while the density increases to 0.240 g/cm^3. The solid clay particles might have been finely dispersed through air spaces within the Kapok wool thereby preventing heat transfer by convection through the air in the void spaces as well serving as reinforcement. And subsequent increases in clay content (Kapok Wool to Clay ratio 2:2.5) reduces the thermal conductivity while it increases sample density. Reduction in thermal conductivity was also noted at Kapok Wool to Clay ratio 2:3.5. This may be due to the evacuation of air in the space within the Kapok wool due to increasing clay content which could have reduce the effective thermal conductivity of the system as supported by Incropera et al. (2007) report. The stress at yield and the modulus of elasticity of the samples were found to increase with increasing clay content in sample. Since clay also served as binder thereby binding the loose Kapok wool together and improve its strength. Results show that the Stress at Yield of samples range from 0.012 N/mm^2 to 0.022 N/mm^2 before failure while the Young Modulus of elasticity range from 0.113 N/mm^2 to 0.222 N/mm^2 before failure.

The addition of clay in order to enhance the thermal properties showed on the average the decrease in thermal conductivity which is good because it indicated that the proposed materials produced are good insulators. Samples with high thermal resistivity are desirable for insulation purposes. Thermal diffusivity was found to decrease which is good because materials with high thermal diffusivity adjust rapidly to ambient temperature because heat is quickly connected. Materials of high thermal diffusivity will respond quickly to changes in their thermal environment, while materials of small thermal diffusivity will response more sluggishly, taking longer to reach a new equilibrium condition (Incropera et al., 2007).

4 Conclusion

This study investigated the effects of varying proportion of clay contents mixed with Kapok wool on thermal and mechanical properties of materials produced. In this way, Kapok wool which is loose in nature have been processed to form rigid or semi-rigid insulation materials. Kapok wool – Clay combination of ratio 2:3.5 (Sample E) appear to have the highest value of thermal resistivity of 76.923 mKW^{-1} and lowest thermal diffusivity of 0.2810 x 10^{-3} m^2/s, though with high density, which suggests it to be the best material among samples in the study for insulation purposes. While Kapok wool – Clay combination of ratio 2:1.5 (sample B) having thermal resistivity of 37.037 mKW^{-1} is the least in the group. The results obtained shows the possibility of having a combination of two different insulation materials (Kapok wool and Clay) to have desired thermal properties and strength. This study has established that the Kapok wool-Clay mixture is a possible solution to meet insulation needs, and the insulators produced have a lower-cost of production and sustainable. The insulation materials produced can be use in thermal storage for medium temperature applications.

Corresponding author's e-mail address: abdulrahimat@unimaid.edu.ng

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