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INVESTIGATION OF THERMAL INSULATION PROPERTIES OF BIOMASS COMPOSITES

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ABSTRACT

This paper reports on the investigation of thermal properties of Kapok, Coconut fibre and Sugarcane bagasse composite materials using molasses as a binder. The composite materials were moulded into 12 cylindrical samples using Kapok, Bagasse, Coconut fibre, Kapok and Bagasse in the ratios of (70:30; 50:50 and 30:70), Kapok and Coconut fibre in the ratios of (70:30; 50:50 and 30:70), as well as a combination of Kapok, Bagasse and Coconut fibre in ratios of (50:10:40; 50:40:10 and 50:30:20). The sample size is a 60mm diameter with 10mm – 22mm thickness compressed at a constant load of 180N using a Budenberg compression machine. Thermal conductivity and diffusivity tests were carried out using thermocouples and the results were read out on a Digital Multimeter MY64 (Model: MBEB094816), while a Digital fluke K/J thermocouple meter PRD-011 (S/NO 6835050) was used to obtain the temperature measurement for diffusivity. It was observed that of all the twelve samples moulded, Bagasse, Kapok plus Bagasse (50:50), Kapok plus Coconut fibre (50:50) and Kapok plus Bagasse plus Coconut fibre (50:40:10) has the lowest thermal conductivity of 0.0074, 0.0106, 0.0132, and 0.0127 W/(m-K) respectively and the highest thermal resistivity. In this regard, Bagasse has the lowest thermal conductivity followed by Kapok plus Bagasse (50:50), Kapok plus Bagasse plus Coconut fibre (50:40:10) and Kapok plus Coconut fibre (50:50).

Keywords: Composite materials; Lagging; Thermal conductivity; Thermal diffusivity; Thermal resistivity

1. INTRODUCTION

Synthetic fibre composites are being replaced by environmental friendly materials, such as natural fibre (wood, banana peels, cotton, coconut fibre, sisal, jute). This is because natural fibre composites have low weight, density, cost, renewable without skin irritations (Ayugi, 2011). They have low to zero toxin ratings, easy to reuse and dispose with significant health benefits (Andy, et al., 2011). This work investigates the thermal insulation properties of agricultural wastes made into composites. These materials are used due to: (a) Overdependence on synthetic fibres, used at a high cost compared to ever available agricultural wastes; (b) Heaith hazard of synthetic fibre when in contact with body; and (c) Low utilization of

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agricultural waste resulting in environmental pollution. Composite materials are cohesive structures made by physical combination of two or more compatible materials, different in their composition and characteristics (Chandramohan & Marimuthu, 2011).

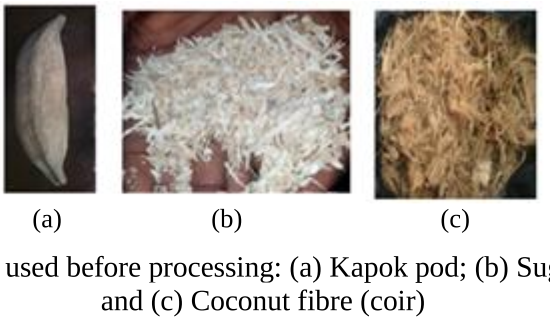
Many literatures have reported on the thermal conductivity of composites, but limited work is reported on agricultural wastes. Ayugi et al., (2011) measured the thermal properties of Sugarcane bagasse, Clay, Kaolin, Ash, Banana fibre, Sawdust and Charcoal dust. They measured conductivity, thermal diffusivity and specific heat capacity and concluded that sugarcane bagasse gives the best thermal insulation for Thermal Energy Storage (TES) systems, since it has the lowest thermal conductivity and highest specific heat capacity against other agricultural wastes. Kyauta et al., (2014) investigated the thermal properties of composite rice husks, sugarcane bagasse and corncob. They observed that samples with a high percentage of rice husks, followed by bagasse and corncobs have the lowest thermal conductivity and the highest thermal resistivity. Lister (2010) explored the potential for the use of agricultural waste as a material for thermal insulation, taking bagasse and coconut coir as a case study.

In this work, kapok, sugarcane bagasse and coconut fibre which are rarely available in literature are formed into a composite for thermal application purposes. Coconut, sugarcane fibre, cotton, wheat straw, palm leaves, oil palm fibre consist of lignocelluloses fibres that are biodegradable, renewable, environmentally friendly building thermal insulators (Ramesh, et al., 2014; Mohammad, 2005).

2. MATERIALS AND METHODS

2.1. Materials Preparation

The materials used in this study are agricultural wastes, except kapok (Figure 1a) obtained from kapok tree. The agricultural wastes are Sugarcane Bagasse (Figure 1b) and Coconut fibre (coir) (Figure 1c). Kapok consist of unicellular fibres, like cotton, and it has a thermal conductivity (λ) of $0.035 W/m^{-1}K^{-1}$ (Ayugi et al., 2011). Sugarcane bagasse is a fibrous leftover obtained after extraction of sugarcane with thermal conductivity ranges from $0.046–0.051 W/m^{-1}K^{-1}$ (Ramesh et al., 2014; Satta & Steve, 2008). Coconut fibre (coir) is a natural fibre extracted from the husk of coconut; it is the fibrous material found between the hard, internal shell and the outer coat of a coconut (Wikipedia, 2014). It has a low thermal conductivity of between $0.054–0.143 W/m^{-1}K^{-1}$ (Ayugi et al., 2011). Molasses (Sodium Silicate) ($Na_2(SiO_3)_nO$) was used as binder. Sugarcane bagasse was reduced to 4mm particle size using a plastic grater, the grated bagasse was sieved with a 2.35 mm hole size, after which it was blended to obtain particle sizes of 0.71 mm after further sieving (Figure 2a). The kapok (Java cotton) (Figure 2c) was removed from its pod (Figure 1a) and hand picking of the kapok seed in the kapok wool/cotton was done. The coconut fibre (Figure 1c) was removed from the coconut husk**,** cleaned and straightened by wire brush to remove unwanted materials**.** The coconut fibre was blended to a size of 2.35 mm, and sieved to 0.71 mm (Figure 2b).



(a) (b) (c)

Figure 1 Materials used before processing: (a) Kapok pod; (b) Sugarcane bagasse; and (c) Coconut fibre (coir)

(a) (b) (c)

Figure 2 Materials after processing: (a) Sugarcane bagasse (0.71mm); (b) Coconut fibre (0.71mm); and (c) Kapok wool/cotton

2.2. Preparation of Composite Materials

Six samples of the materials were prepared (Table 1). Samples A, B, C are 100% of the materials and Samples D, E and F are mixture of the materials in different percentage (Tables 1 and 2). The samples were prepared into cylindrical shapes of thickness (t), radius (R) and volume, V given by Equation 1.

$$V = \pi R^2 t \ (m^3) \qquad (1)$$

A 60 mm diameter metal mould (Figure 3) was used to mould the biomass after mixing with 80% by mass of the binder. The mixture was poured into the mould and compressed by a load of 180 N (Figure 4). The sample was left for five minutes in the mould and oven dried for 9 hours at 105°C. A total number of 12 samples were produced (Figure 5).

Table 1 Sample designation

No.	Samples	Materials
1	A	Kapok
2	B	Bagasse
3	C	Coconut Fiber
4	D	Kapok + Bagasse
5	E	Kapok + Coconut Fibre
6	F	Kapok + Bagasse + Coconut Fibre

Table 2 Percentage composition by weight of samples

S/NO	Samples	Kapok	Bagasse	Coconut fibre
		SAMPLE D		
1	D1	70%	30%	-
2	D2	50%	50%	-
3	D3	30%	70%	-
		SAMPLE E		
4	E1	70%	-	30%
5	E2	50%	-	50%
6	E3	30%	-	70%
		SAMPLE F		
7	F1	50%	40%	10%
8	F2	50%	10%	40%
9	F3	50%	30%	20%

Figure 3 Metal mould used

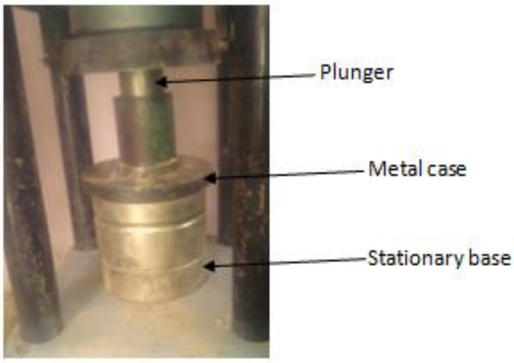


Figure 4 Biomass composite under Compression

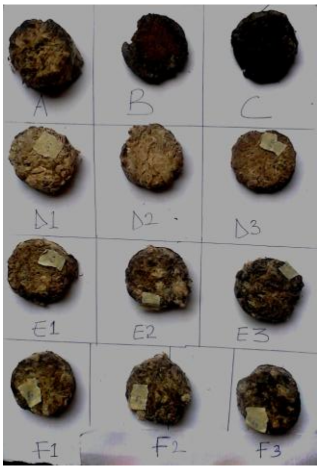


Figure 5 Moulded biomass composites

2.3. Determination of Thermal Insulation Property

2.3.1. Determination of sample density

The density of the sample was obtained from Equation 2.

$$Density = \frac{Mass\ (kg)}{Volume\ in\ (m^3)} \tag{2}$$

2.3.2. Determination of percentage moisture content

Percentage moisture content was obtained by the difference between the wet weight (W_1) and dry weight (W_2) of the sample, using Equation 3.

Moisture content (g) = $W_1 – W_2 = \Delta W$

$$\text{Percentage moisture content} = \frac{Moisture\ Content}{Wet\ Weight} \times 100 = \frac{\Delta W}{W_1} \times 100 \tag{3}$$

2.3.3. Determination of thermal conductivity

The thermal conductivity (κ) of any material is a measure of its effectiveness in conducting heat (Gesa et al., 2014; Ramesh et al., 2014). Thermal conductivity was determined using heat transfer from the heat source to the sample (Figure 6). Prior to the determination of thermal conductivity, thermal history of individual material was determined. The thermal conductivity tests (Figure 7) was conducted in line with ASTM E1530-11 (Eeday et al., 2014; Rodriguez et al., 2011; Zhou et al., 2010; Satta & Steve, 2008; Manohar et al., 2006). The thermal properties of the materials were established using steady-state, one-dimensional condition. The method is based on the principle of hot wire in which a heat pulse is supplied to the sample and the increase in temperature recorded by thermocouple (Tripathi et al., 2016; Eeday et al., 2014; Rodriguez et al., 2011). Type K (Chromel-Alumel) thermocouple and a Mastech Digital Multimeter MY64 (Model MBEB094816) were connected to cold and hot ends of the specimen as well as the center to measure the temperature (Rodriguez et al., 2011). The thermocouple was connected to 1800 watt heat source, and inserted into the sample at the middle (Figure 6). The Chromel wire at 2 cm depth was to measure the surface temperature of the sample, while Alumel was connected through the base of the sample at a depth of 2 cm. The temperature was recorded at 30 second intervals and the total time used per sample was 5 minutes. The thermal conductivity was obtained by Equation 4.

$$Q = \frac{KA\Delta T}{\Delta L} \quad (4)$$

where, K is the thermal conductivity (w/m/k), A is the cross-sectional area of the sample (m^2), ΔL is the distance between the two wires of the thermocouple, ΔT is the temperature (k), and Q is the quantity of heat supplied (Watt).

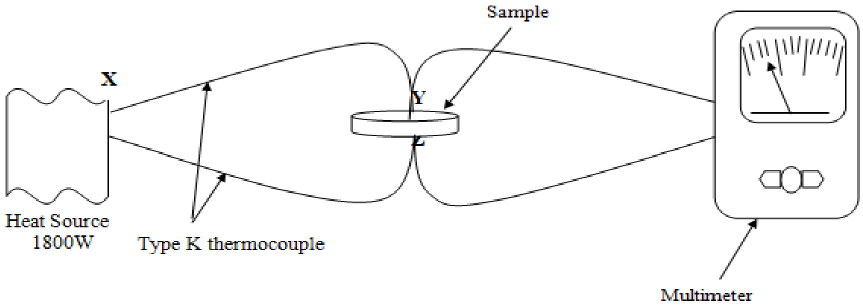


Figure 6 Schematic diagram of thermal conductivity experiment

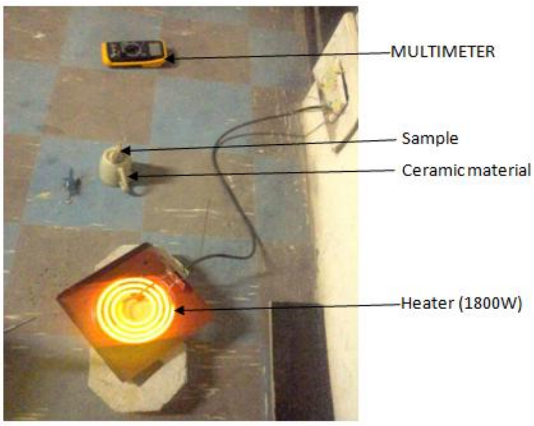


Figure 7 Setup of thermal conductivity test

2.3.4. Determination of thermal resistivity

Thermal resistivity is the resistance of a material to the flow of heat (Satta & Steve, 2008). It can be expressed mathematically by Equation 5:

$$\text{Resistivity} = \frac{1}{k}\,(w^{-1}mk) \quad (5)$$

2.3.5. Determination of thermal diffusivity (α)

Thermal diffusivity of the developed material according to ASTM E1461-13 (ASTM, 2010; Zhou et al., 2010) was determined by thermocouple experiment (Figure 8) using Type J -Iron Constantan and Type K- Chromel Alumel. Fluke 52 K/J digital Thermometer-PRD-011 (serial no 6835050) was used to measure change in temperature at a time interval of 30 seconds. One end of thermocouple was inserted into the digital thermometer and the other end inserted into the sample. In thermal diffusivity test, an 1800 watt electric heater serves as heat source and atmospheric condition as cold source. A metal plate placed on the heat source while the sample was placed on the metal plate (Figure 9).

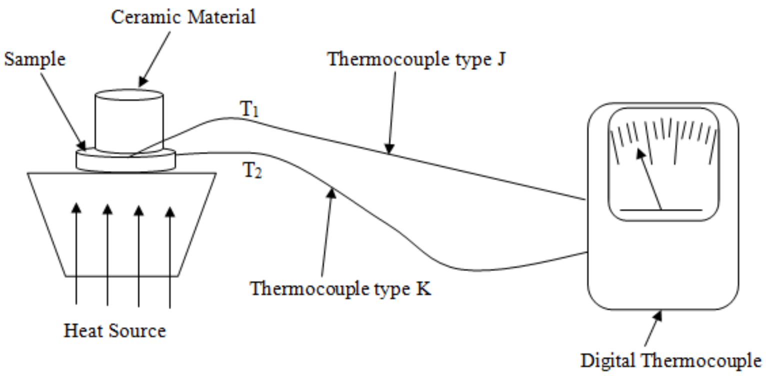


Figure 8 Schematic diagram of thermal diffusivity

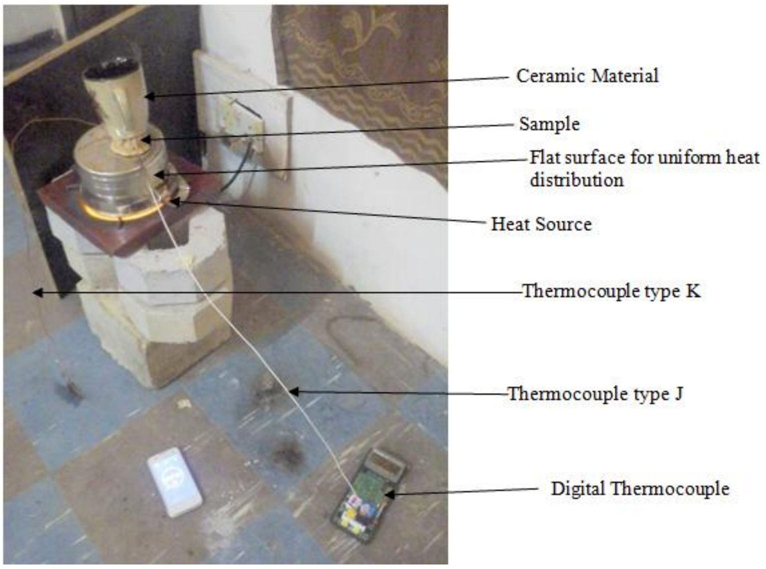


Figure 9 Experimental setup

A Type K thermocouple was inserted 2 cm depth below the sample to measure the temperature (T_1) due to the heat from the hot metal to the base of the sample. Type J thermocouple was placed on the surface of the sample at a depth of 2 cm to measure the surface temperature (T_2). Ceramic material was used as insulator and as a load application to press the samples onto the metal plate for uniform distribution of heat and to prevent air gap between the samples and the metal plate. Temperature T_1 and T_2 was measured and recorded every 30 seconds until a constant temperature was attained. The graph of the natural logarithm of change in temperature (InδT) against the reciprocal of time *t* was plotted and the slope is obtained by Equation 6. The thermal diffusivity is calculated using Equation 7.

$$\text{Slope} = \frac{\ln\delta T}{1/t} \quad (6)$$

$$\text{Thermal diffusivity} \quad \alpha = -\frac{x^2}{4slope} \; (m^2/s) \quad (7)$$

2.3.6. Determination of specific heat capacity (C)

It is measured in J/kg.k, and obtained mathematically from the Finite Approximation Equation that relates the thermal conductivity, thermal diffusivity and density of the sample (Zhou et al., 2010). It can be shown mathematically by Equation 8:

$$\text{But } C = \frac{k}{\alpha\rho} \quad (8)$$

where α is the thermal diffusivity (m^2/s), ρ is the density of sample, k is the thermal conductivity

3. RESULTS

3.1. Thermal Behaviour of the Base Materials

Figures 10, 11 and 12 show the thermal conductivity, thermal diffusivity and thermal resistivity of Kapok, Bagasse, Coconut fibre and Kapok with Bagasse. It can be observed (Figure 10) that Kapok, Sugarcane Bagasse, Coconut fibre and Kapok with Bagasse had a steady increase in thermal conductivity with temperature and time. All the materials after 4 minutes experienced slight reduction in their conductivity. Kapok, Coconut fibre, Kapok with Bagasse and Bagasse show higher thermal conductivity in that order respectively. The thermal diffusivity property (Figure 11) of Kapok, Bagasse, Coconut fibre and Kapok with Bagasse show initial stability for the first 2 minutes. An increase in diffusivity for all the samples after 2 minutes is observed. At 3 minutes stability in thermal diffusivity is observed for all the four samples up to the end of the 5-minute test period. Figure 12 shows bagasse having a sharp decrease in resistivity in the first 2 minutes with a slight and steady decrease in resistivity up to 4 minutes after which there is an increase in thermal resistivity. Kapok and Kapok plus Bagasse show a fairly stable thermal resistivity property with temperature and time. A slight decrease and increase in diffusivity was observed for Kapok and Kapok plus Bagasse respectively in the first 2 minutes. The Coconut fibre shows an unstable behavior in its thermal resistivity properties. A very slight increase and decrease is observed between 1 and 3 minutes with slight increase up to the 5 minutes of the test period (Figure 12).

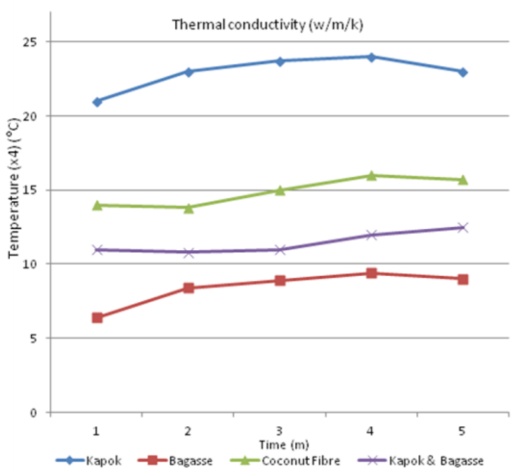


Figure 10 Thermal conductivity of base materials

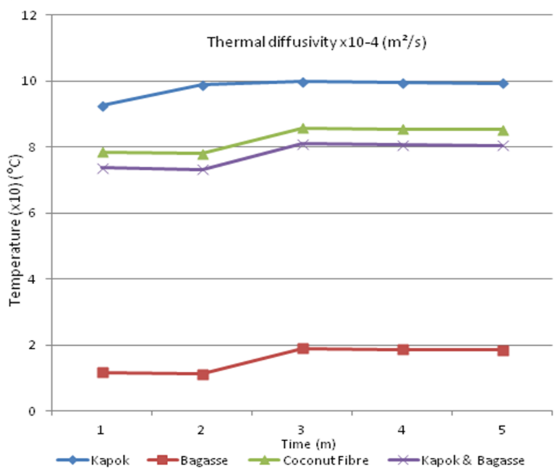


Figure 11 Thermal diffusivity of base materials

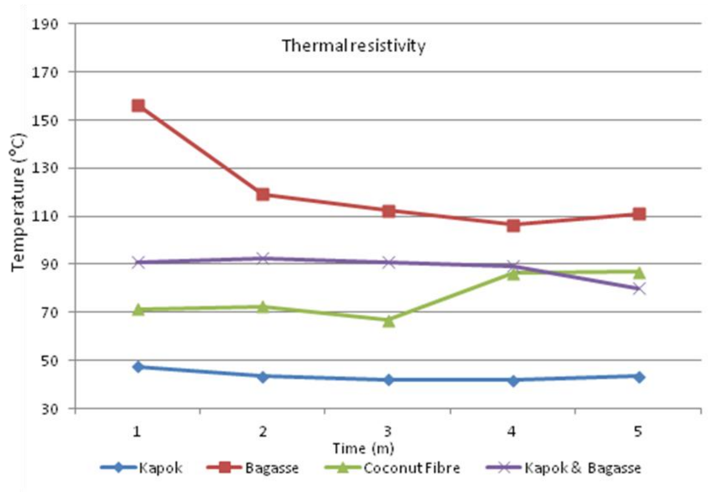


Figure 12 Thermal resistivity of base materials

3.2. Thermal Behaviour of the Biomass Composite Material

The results of thermal conductivity, thermal diffusivity, specific heat capacity and resistivity tests are shown in Table 3. Figure 13 shows the thermal diffusivity of the samples.

Table 3 Thermal properties of various biomass samples

Sample	Compressed density (kg/m^3)	Relaxed Density (kg/m^3)	Thermal conductivity (w/m/k)	Thermal diffusivity (m^2/s) ×10^{-4}	Thermal resistivity	Specific heat capacity (J/kg/k)
A	1.173	0.723	0.0220	9.67	45.45	31.50
B	1.485	0.778	0.0074	1.58	135.14	60.20
C	1.143	0.626	0.0109	8.26	91.743	21.08
D1	1.149	0.707	0.0139	7.78	71.94	25.28
D2	1.360	0.843	0.0106	19.98	94.34	6.29
D3	1.465	0.758	0.0130	5.05	76.92	33.96
E1	1.260	0.707	0.0143	10.91	69.93	18.54
E2	1.415	0.825	0.0132	9.16	75.76	17.47
E3	1.320	0.802	0.0134	4.62	74.60	36.17
F1	1.440	0.884	0.0127	15.72	78.94	17.65
F2	1.216	0.663	0.0159	5.87	62.90	40.86
F3	1.394	0.894	0.0174	15.42	57.47	12.62

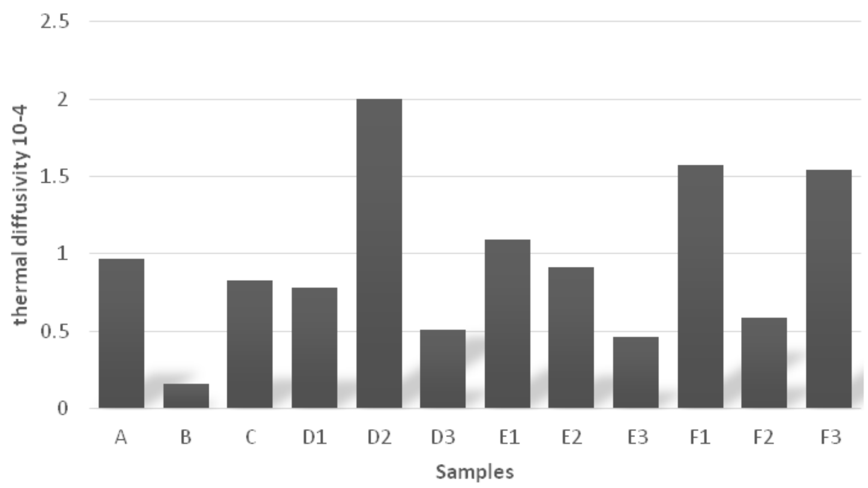


Figure 13 Thermal diffusivity of the developed biomass materials concentration at a constant temperature

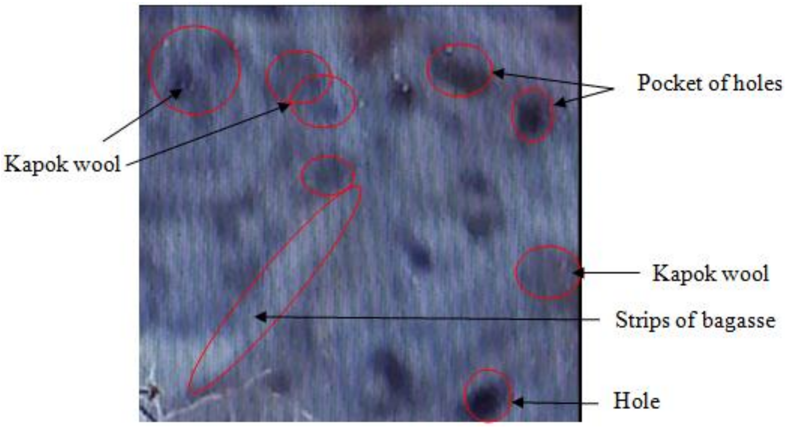


Figure 14 Micrograph of bagasse-Kapok interwoven structure showing pocket of holes (×150)

4. DISCUSSION

The characteristics of thermal conductivity of Kapok displayed in Figure 10 were as a result of the loose fibrous nature of Kapok that enhances its conductivity. It is likely that due to uneven nature of the condensed strands that exist in Bagasse resulted in its fair conductivity properties. The properties exhibited by the Coconut fibre were likely to be responsible for its laminated uncondensed fibre that naturally exists. Kapok with Bagasse has the properties of a loose fibrous nature, coupled with condensed strands that make the material have a fairly stable temperature compared to the other three base materials (Figure 10). For the thermal diffusivity properties (Figure 11), other than Kapok that has a fairly stable diffusivity primarily due to its loose woolly structure, other base materials exhibited same trends in their diffusivity. The thermal resistivity characteristics plotted in Figure 12 indicates that Coconut fibre has the least resistivity against Kapok with Bagasse, which has a stable resistivity among the base materials.

From the results obtained (Table 3), it can be observed that Sample A (Kapok) has the highest thermal conductivity value, followed by Sample C (Coconut fibre) and Sample B (Bagasse). Sample B has the lowest thermal conductivity of 0.0074 w/m/k which is similar to the work of Ayugi et al. (2011), where they carried out thermal insulation properties tests on seven agricultural wastes. These tests indicated that sugarcane bagasse has the best thermal insulation properties, which makes it suitable as a lagging material. For Sample D (kapok with sugarcane bagasse), Sample D1 has the highest thermal conductivity followed by Samples D3 and D2. Sample D2, which contained 50% kapok and 50% bagasse had the lowest thermal conductivity, due to the equal percentage of materials.

The low thermal behaviour of Sample D2 may likely be responsible to the low thermal behaviour of Bagasse, which has a flake-like structure that is interwoven into the kapok, resulting in more air gaps in their structure (Figure 14). In a similar trend, Sample E2, which has 50% kapok and 50% coconut fibre, has the lowest thermal conductivity among the Sample E group. Sample F1, which is 50% kapok 40% bagasse and 10% coconut fibre and has the lowest thermal conductivity, similar to the work of Kyauta et al. (2014). The behaviour of low thermal conductivity of Sample F1 could be linked to the effect of both bagasse and coconut fibre, which create more air space within the kapok interface, due to their combined effect. This shows that kapok, which has the highest thermal conductivity when used alone works better when combined with other materials at 50% and also the structure of coconut fibre and that of bagasse help to reduce heat flow as they were able to mix and form a good thermal resistance. The thermal conductivity of the materials used in this study has a minimum value of 0.0106 (w/m/k) for Sample D2 and a maximum value 0.022 w/m/k for Sample A, which shows better thermal properties, when compared to Isorel with 0.4498 w/m/k and P.O.P with 0.1185 w/m/k as reported by Gesa et al. (2014). Thermal resistivity is the inverse of thermal conductivity (i.e. at low conductivity there is a corresponding high resistivity). It is observed from Table 3 that Samples B, D2, E2 and F1 have the highest thermal resistivity values in their respective categories, revealing that they have high resistance to heat, which implies that they respond to heat flow slowly. Thermal diffusivity of the samples was obtained by using the slope of the plot of change in temperature against the inverse of time (Figure 13). The diffusivity was obtained in an order of $\times 10^{-4}$ m^2/s, which shows that all the samples have low temperature response to heat pulse and the behaviour makes them suitable as lagging materials.

5. CONCLUSION

The following conclusions were drawn from the investigation of thermal insulation properties of biomass composites: (1) Kapok works better (good thermal insulator) when combined with Coconut fibre and Bagasses at a percentage of 50%; (2) The particle size of Coconut fibre and that of Bagasse helps reduce heat flow, hence they serve as good thermal resistance materials; (3) All the samples investigated in this work can withstand a medium temperature range of 150^oC to 450^oC; (4) Sample B (Sugarcane Bagasse), Sample D_2 (Kapok and Bagasse 50:50), Sample E_2 (Kapok and Coconut fibre 50:50) and Sample F_1 (Kapok, Bagasse and Coconut fibre 50:40:10) can be used for a high temperature application range of above 450^oC.

6. ACKNOWLEDGEMENT

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