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A Comparison of Banana Fiber Insulation with Biodegradable Fibrous Thermal Insulation

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ABSTRACT: *Environmental concern about the disposal of discarded thermal insulation focused research in developing new and innovative biodegradable materials to facilitate and improve the thermal demands of society. Banana fiber is a lignocellulose material derived from the discarded tree trunk and can be a cheap, abundantly available, reliable, biodegradable and renewable raw material source. Thermal conductivity measurements on 50.4 mm thick slab-like banana fiber specimens showed characteristics consistent with that of fibrous thermal insulation. An empirical correlation developed to predict the apparent thermal conductivity variation with density and mean test temperature showed values within 4% of the experimental results. Comparison of the thermal conductivity at 25^{o}C and at the optimum density for coconut fiber, sugarcane fiber and oil palm fiber with banana fiber indicated that they were all within the range of 0.02 W/m.K to 0.06 W/m.K for use as building thermal insulation. Of the four lignocellulose materials considered, banana fiber showed the lowest thermal conductivity value of 0.04415 W/m.K at a density of 70.4 kg/m^{3}compared to 0.0488 W/m.K at a density of 69.57 kg/m^{3}for coconut fiber, 0.0483 W/m.K at a density of 95.94 kg/m^{3}for sugarcane fiber and 0.0572 W/m.K at a density of 100.30 kg/m^3 for oil palm fiber.*

Keywords: *Banana fiber, biodegradable insulation, building insulation, renewableinsulation, thermal conductivity.*

I. INTRODUCTION

The primary function of building thermal insulation is to reduce unwanted heat gain or heat loss across the building envelope thereby contributing to the thermal comfort of the occupants. The reduction in heat gain is reflected in the reduced energy demand for cooling or heating in buildings which translates into reduced greenhouse gas emissions [1]. Generally, building thermal insulation are materials with low thermal conductivity within the range 0.02 W/m.K to 0.06 W/m.K [2]. Loose-fill fibrous materials that traps air within the pores are generally used for thermal insulation as it provides a low apparent thermal conductivity at a relatively low density [3, 4]. In the recent past, growing environmental concern focused research in developing new and innovative biodegradable thermal insulation to facilitate and improve the thermal demands of society.

The lignocellulose composition of plant fiber has the structure and properties for use as composite textile material and in the manufacture of pulp and paper. Also, plant based fibrous waste are used to produce fuel, chemicals, enzymes and animal food. Approximately 2 x 10^{11} tons of plant base lignocellulose are produced every year compared to 1.5 x 10^8 of polymer fiber [5]. This material source is renewable annually, abundantly available, presently is of little value and can be a cheap raw material source for downstream industries [6].Published work indicated that materials such as coconut fiber, sugarcane fiber, cotton, wheat straw, date palm leaves, oil palm fiber and other lignocellulose fibers are promising alternatives for use as biodegradable, renewable, environmentally friendly building thermal insulation [7, 8, 9]. Development of biodegradable thermal insulation to perform comparable to the non-biodegradable insulation will mitigate the environmental issues presently faced.

Banana is a tropical plant and is one of the most common fruit grown and is among one of the most eaten fruit in the world [10]. The banana tree trunk is a soft leaf-like material, high in fibrous content. In the banana tree the long fibers represent approximately 1.5% by total mass of the plant [11, 12]. After removing the bananas, the leaves and trunk is discarded. In the commercial production of bananas, the large number of trees incur extra cost to the farmer for disposal since only a limited amount of the tree can be used in the plantations as organic fertilizer[4].

Research on the thermal insulating properties of plant base lignocellulose materials such as coconut fiber, sugarcane fiber and oil palm fiber showed promising insulating characteristics for use as building thermal insulation. At the optimum density the thermal conductivity these materials were within the range for use as building thermal insulation [13, 14]. The comparatively long banana fiber is an attractive alternative for use as building thermal insulation. The long fibers can be easily woven into a flexible slab-like batt without the use of any binding material. However, use as thermal insulation will depend on the thermal conductivity at the optimum density and comparative to other lignocellulose materials. If managed effectively, banana fibers can serve as a renewable biodegradable thermal insulation with a net reduction in CO_2 emissions over the life cycle[2]. A cheap, reliable and abundant supply of banana fiber can be obtained as waste by-products from the commercial banana industries. The main indicator of the quality of an insulating material is the apparent thermal conductivity [14]. The apparent thermal conductivity of a loose-fill fibrous material varies with bulk density and the optimum density at which minimum thermal conductivity is exhibited is required for best thermal and economical use of the material[15]. In this study the variation of thermal conductivity with bulk density of banana fiber is investigated for use as building thermal insulation and compared with the thermal conductivity of other lignocellulose thermal insulation.

II. BANANA FIBER SAMPLE PREPARATION

Research indicated that thus farthere are no commercial means of extracting banana fibres as the demand is low and buyers of banana fiber are erratic, but there are experimental projects that use rotary type machines to extract natural fibers [16].An experimental slotted-barrel rotating machine in the Agricultural Engineering Laboratory at The University of the West Indies was used to extract the banana fibre (Fig. 1).

Figure 1. Slotted-barrel rotating machineused to extract the banana fibre

The outer layers of the banana tree trunk was peeled off and cut into strips 10 to 15 cm width for processing in the machine (Fig. 2). The innermost part of the banana trunk was not used as it contained softer fibres.

Figure 2. Banana trunk strips for processing

The exposed fibers (Fig. 3)were then allowed to air dry for seven days under laboratory conditions after which the fibres were cut and sorted.

Figure 3. Processed banana strips showing exposed fiber

Slab-like experimental test specimens 50.4 mm thick and 254 mm square of varying densities were prepared. The fibres were randomly packed in a polystyrene specimen holder constructed with 25.5 mm thick polystyrene strips, 50.4 mm high with a thin polythene base to hold the fibres in place (Fig. 4).

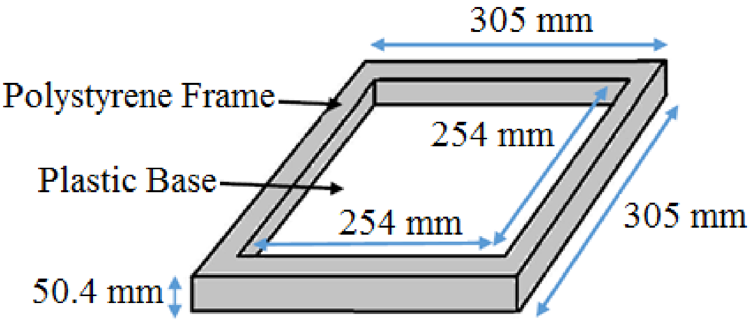

Figure 4: Polystyrene specimen holder

The density was varied by calculating the required fiber mass from the known specimen holder volume and the target density. The minimum fibre density of 20 kg/m^3 was determined by allowing the randomly arranged fibre specimen to settlenaturally. Test specimens were then prepared for density ranging from 20 kg/m^3 to 120 kg/m^3 in increments of 10 kg/m^3. The maximum test density was determined by the clamping for of the test apparatus.

III. BANANA FIBER EXPERIMENTAL RESULTS

Thermal conductivity measurements were conducted in accordance with ASTM C-518-04, Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus. The test apparatus used was the LaserComp FOX 304 steady state thermal conductivity measurement meter. The meter was calibrated using NIST SRM 1450b, Standard Reference Material of the National Institute of Standards and Technology with a 20^{o}C temperature difference between the plates and upward heat flow. The heat flux transducer of size 102 mm x 102 mm was centrally located on the constant temperature plates. Prepared specimens of respective densities were placed in the test apparatus and the mean test temperature set between 20^{o}C to 40^{o}C, in increments of 5^{o}C with a 20^{o}C temperature difference between the hot and cold plates. The FOX 304 provided thermal conductivity measurements within the range 0.005 W/m.K to 0.35 W/m.K with ± 0.2% repeatability and ± 0.5% reproducibility(Fig. 5) [17]. The heat sink for the FOX 304 was provided by an independent chilled water system and a circulating pump.

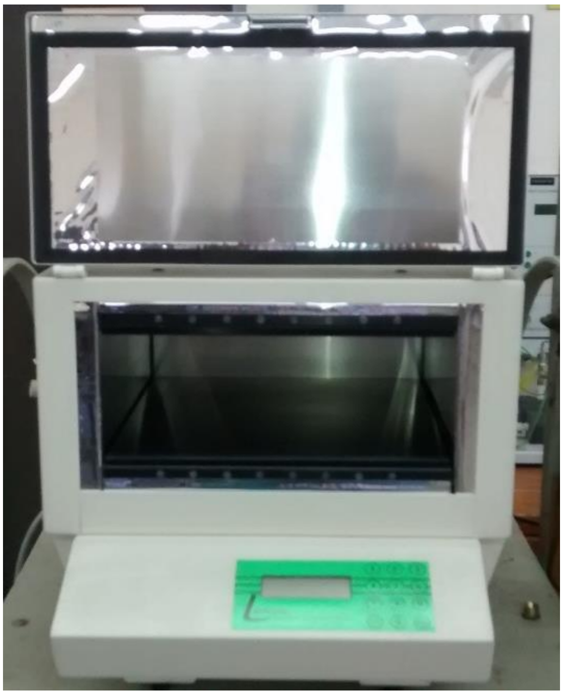

Figure 5. LaserComp FOX 304 in open position

The test apparatus was closed and the system not disturbed until all set points were tested. The apparatus switched automatically from one set point to the other when the test was completed at one set point. The test specimen was then changed and the test procedure repeated for the next density. The experimental progress was continuously monitored via the computer link and the results recorded and stored automatically.Thermal conductivity measurements were conducted on 50.4 mm thick slab-like banana fibre specimens at mean test temperatures of 20°C, 25°C, 30°C 35°C and 40°C with a 20°C temperature difference between the hot and cold constant temperature plates. The density of the banana fibre specimens tested were 20kg/m^3, 30kg/m^3, 40kg/m^3, 50kg/m^3, 60kg/m^3, 70kg/m^3, 80kg/m^3, 90kg/m^3, 100kg/m^3, 110kg/m^3 and 120kg/m^3. The thermal conductivity test results are shown on Table 1.

Table 1: Banana Fibre Experimentally Determined Thermal Conductivity with 50.4 mm thick specimen

Density (kg/m^3)	**Experimental Determined Thermal Conductivity (W/m.K)**				
	20 °C	**25 °C**	**30 °C**	**35 °C**	**40 °C**
20	0.06679	0.06902	0.07135	0.07367	0.07533
30	0.05341	0.05499	0.05679	0.05855	0.05939
40	0.04816	0.04935	0.05096	0.05264	0.05395
50	0.04612	0.04674	0.04747	0.04850	0.04985
60	0.04355	0.04443	0.04520	0.04576	0.04677
70	0.04231	0.04392	0.04611	0.04567	0.04648
80	0.04202	0.04275	0.04436	0.04484	0.04495
90	0.04389	0.04466	0.04529	0.04593	0.04495
100	0.04496	0.04509	0.04573	0.04607	0.04523
110	0.04647	0.04667	0.04740	0.04839	0.04958
120	0.04854	0.04921	0.05013	0.05141	0.05248

IV. DATA ANALYSIS

The experimental results (Tables 1) for the 50.4 mm thick loose-fill banana fibre specimens at the five respective mean test temperatures all showed a decrease in thermal conductivity with increase in density to a minimum value and then increase in thermal conductivity with further increase in density [9, 13, 18, 19]. This trend is associated with the behaviour of loose fill thermal insulation and therefore, the thermal conductivity, λ, variation with density should satisfy the general empirical relationship associated with this characteristic behaviour for materials of this nature as given by equation (1) [9, 20].

$$\lambda = a + b\rho + c/\rho \qquad (1)$$

Where λ is thermal conductivity in W/m.K, ρ is density in kg/m^3, and a, b, c are numerical constants.

Using the Method Least Squares the banana fibre experimental data for each test condition was fitted in the form of equation (1) and the constants determined. This resulted in an empirical correlation for each test condition as shown in equations (2) to (6).

At 20 ˚C mean temperature;
$\lambda = 0.01587 + (0.19805 \text{ x } 10^{-3})\rho + 0.9468/\rho$ (2)
At 25 ˚C mean temperature;
$\lambda = 0.01646 + (0.19436 \text{ x } 10^{-3})\rho + 0.9798/\rho$ (3)
At 30 ˚C mean temperature;
$\lambda = 0.01740 + (0.19150 \text{ x } 10^{-3})\rho + 1.0079/\rho$ (4)
At 35 ˚C mean temperature;
$\lambda = 0.01401 + (0.22607 \text{ x } 10^{-3})\rho + 1.1186/\rho$ (5)
At 40 ˚C mean temperature;
$\lambda = 0.01615 + (0.20359 \text{ x } 10^{-3})\rho + 1.1154/\rho$ (6)

The linear variation of thermal conductivity (λ)with mean test temperature can be represented with a straight line equation of the form
$\omega(T) = \text{d} + \text{e}.T$ (7)
where $\omega(T)$ is an expression for the temperature dependence, d and e are numerical constants , and T is the mean test temperature.

Using the Method of Least Squares to incorporate the linear increase in thermal conductivity with mean test temperature resulted in a general empirical correlation in the form of equation (8) for determining λ in terms of temperature and specimen density for the banana fibre specimens.
$\lambda = (0.01712 - 0.381 \text{ x } 10^{-4}\,T) + (0.177 \text{ x } 10^{-3} + 0.8556 \text{ x } 10^{-6}\,T)\,\rho + (0.7482 + 0.9518 \text{ x } 10^{-2}\,T)/\rho$ (8)

At a mean test temperature of 25°C the respective thermal conductivity value was calculated form the general empirical correlations and the percentage difference between the experimental and theoretical λ determined. The results are shown on Tables 2. To determine the optimum density equation (8) was differentiated and set equal to zero. This resulted in a minimum value of λ at 70.4 kg/m^3.

Table 2: Banana Fibre – Calculated and Experimentally Thermal Conductivity at 25°C

Density (kg/m^3)	**Thermal Conductivity W/m.K**		
	Experimental	**Calculated**	**% difference**
20	0.06902	0.06944	0.61
30	0.05499	0.05499	0.00
40	0.04935	0.04876	-1.20
50	0.04674	0.04581	-1.99
60	0.04443	0.04451	0.18
70	0.04392	0.04415	0.51
80	0.04275	0.04437	3.79
90	0.04466	0.04498	0.72
100	0.04509	0.04587	1.73
110	0.04667	0.04696	0.62
120	0.04921	0.04820	-2.06

V. COMPARATIVE LIGNOCELLULOSE MATERIAL THERMAL CONDUCTIVITY

Published work on the thermal conductivity of 52 mm thick coconut fiber reported a minimum value of 0.0488 W/m.K at a mean test temperature of 25°C. The empirical correlation, equation (9), predicted the apparent thermal conductivity variation of coconut fiber with density and temperature and within the range 40 kg/m^3 to 90 kg/m^3 [13].

$\lambda = (0.071232 - 0.003333T) + (-0.000246 + 2.73355 \text{ x } 10^{-5}T)\,\rho + (-0.372006 + 0.099565\,T)/\rho$ (9)
The optimum density of 69.57 kg/m^3 was calculated by setting the differential of equation (9) to zero.

Published work on the thermal conductivity of 52 mm thick sugarcane fiber reported a minimum value of 0.0483 W/m.K at a mean test temperature of 25°C. The empirical correlation, equation (10), predicted the apparent thermal conductivity variation of sugarcane fiber with density and temperature and within the range 70 kg/m^3 to 120 kg/m^3 [13].
$\lambda = (0.038311 - 0.21448 \text{ x } 10^{-2}T) + (0.5166 \text{ x } 10^{-4} + 0.11203 \text{ x } 10^{-4}T)\,\rho + (0.2554 + 0.11193T)/\rho$ (10)
The optimum density of 95.94 kg/m^3 was calculated by setting the differential of equation (10) to zero.

Published work on the thermal conductivity of 52 mm thick oil palm fiber reported a minimum value of 0.05716 W/m.K at a mean test temperature of 25°C. The empirical correlation, equation (11), predicted the apparent thermal conductivity variation of oil palm fiber with density and temperature and within the range 20 kg/m^3 to 120 kg/m^3 [14].

$$\lambda = (0.0424 - 0.370 \times 10^{-4} T) + (1.6468 \times 10^{-5} + 4.1190 \times 10^{-6} T)\,\rho + (0.7541 + 0.0179T)/\rho \qquad (11)$$

The optimum density of 100.30 kg/m^3 was calculated by setting the differential of equation (11) to zero.

A comparison of the empirical equation thermal conductivity of banana fiber with coconut, sugarcane and oilpalm fiber and a plot of the banana fiber experimental data are shown in Fig. 6.

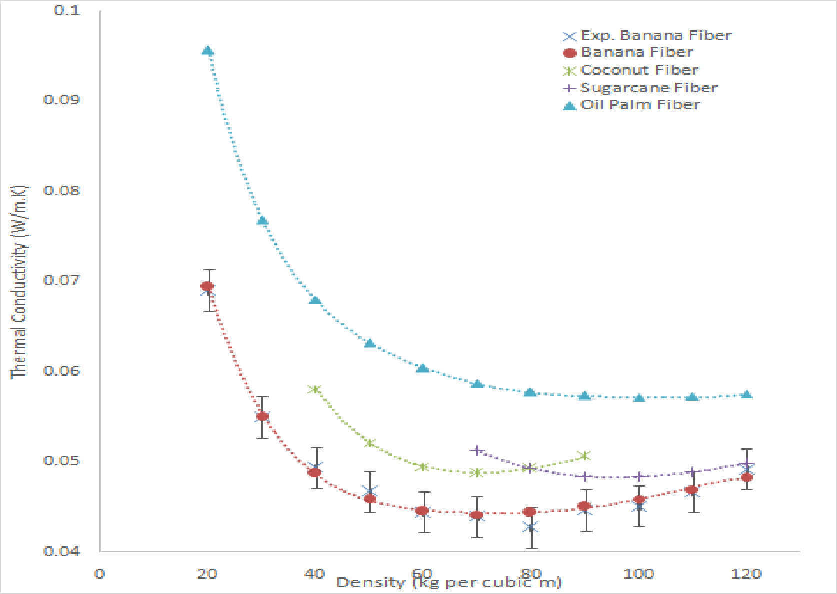

Figure 6. Graph of thermal conductivity variation with density for banana fiber, coconut fiber, sugarcane fiber, oil palm fiber and plot of banana fiber experimental data

VI. DISCUSSION

Experimental test results at mean test temperatures ranging from 20°C to 40°C over the density range 20kg/m^3 to 120kg/m^3 for banana fiber showed the thermal conductivity variation with density followed the characteristic hooked shape associated with loose-fill fibrous thermal insulation. The experimental data indicated the optimum density is within the range 70 kg/m^3 to 90 kg/m^3 as samples were tested in increments of 10 kg/m^3 and the minimum thermal conductivity was reported at 80 kg/m^3.For fibrous insulation thermal conductivity increases with temperature. The experimental test results indicated this trend and at the optimum density of 80 kg/m^3showed an average increase in thermal conductivity of 1.71% for an increase in mean test temperature of 5°C. The general empirical correlation derived to determine the apparent thermal conductivity variation with density and mean test temperature showed values within 4% of the experimental value. Apart from the largest deviation of 3.79% at 80 kg/m^3, the values were within ±2.06%. From the plot of experimental data in Fig. 6, the experimental value at 80kg/m^3 is lower than normal. Taking into account the apparatus error of ±0.5% as shown with the error bar in Fig. 6, the experimental and calculated thermal conductivity values correlated. Comparison of banana fiber with other loose-fill lignocellulose materials of similar thickness at a mean temperature of 25°C showed the banana fiber has the lowest apparent thermal conductivity. Coconut fiber has a minimum thermal conductivity of 0.0488 W/m.K at a density of 69.57 kg/m^3.Sugarcane fiber has a minimum thermal conductivity of 0.0483 W/m.K at a density of 95.94 kg/m^3.Oil palm fiber has a minimum thermal conductivity of 0.0572 W/m.K at a density of 100.30 kg/m^3. Comparatively, banana fiber has a minimum thermal conductivity of 0.04415 W/m.K at a density of 70.4 kg/m^3. The minimum thermal conductivity of all the materials are within the range 0.02 W/m.K to 0.06 W/m.K for use as building thermal insulation, however, of the four lignocellulose fibrous materials banana fiber is the best suited for use building thermal insulation.

VII. CONCLUSION

The thermal conductivity variation with density and mean test temperature of banana fiber is consistent with that of loose-fill fibrous thermal insulations. The empirical correlation developed to predict the apparent thermal conductivity variation with density and mean test temperature showed values within 4% of the experimental results. Of the four lignocellulose materials considered, banana fiber showed the lowest thermal conductivity value of 0.04415 W/m.K at a density of 70.4 kg/m^3. The thermal conductivity of banana fiber is within the range for use as building thermal insulation.

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