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# ANALYZING THE THERMAL INSULATING CHARACTERISTICS OF BANANA FIBER

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## ABSTRACT

Development of biodegradable thermal insulation such as banana fiber to perform comparable to conventional non-biodegradable insulation will mitigate the environmental issues presently faced with disposal. Empirical correlations were developed from experimental data to predict the thermal conductivity variation of banana fiber with density and mean test temperature for 25.4 mm, 38 mm and 50.4 mm thick loose-fill slab-like specimens over the density range 20 kg/m$^3$ to 120 kg/m$^3$ and mean temperature range between 20$^o$C to 40$^o$C. The equations predicted the characteristic behavior of decreasing thermal conductivity to a minimum value with increasing density followed by increasing thermal conductivity with further increase in density for the banana fiber. Also, the empirical correlations showed the linear increase in thermal conductivity with mean test temperature for the banana fiber, consistent with loose-fill thermal insulation. The mean percentage difference between the calculated thermal conductivity values at the respective experimental test conditions and the experimental data were within ±0.2%. The empirical correlations can be used to determine the thermal conductivity of the banana fibre specimens at any combination of mean test temperature and density within the range tested. The results indicated by both the empirical correlations and the experimental data that the minimum thermal conductivity of banana fibre insulation is within range normally associated with building thermal insulation.

**KEYWORDS –** Banana fiber, Building insulation, Fibrous insulation, Loose-fill insulation, Thermal conductivity, Thermal insulation.

## 1. INTRODUCTION

Application of thermal insulation is widely used in industrial and domestic applications. It is the most common mechanism for the reduction of heat transfer rate across a thermal gradient. Presently, for domestic applications the use of inorganic building insulating materials such as mineral wool, plastic foams, lightweight and cellular concrete, polystyrene, foam glass, expanded perlite and fiberglass are commonplace [1]. Effective building thermal insulation is the largest building energy conservation component that directly impact on the cost of cooling. In recent times retrofitting, upgrading and refurbishing of older buildings resulted in an increase in the amount of non-biodegradable insulation material for disposal causing serious environmental concerns. This initiated research in many countries to shift focus to the use of naturally occurring biodegradable fibrous thermal insulation for buildings [2].

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 [3, 4, 5]. Development of biodegradable thermal insulation to perform comparable to the non-biodegradable insulation will mitigate the environmental issues presently faced. Also, if managed effectively, naturally occurring fibrous materials can be obtained from by-products of the agricultural industry and be a cheap, reliable and renewable material source [6]. Over the life cycle of plant base fibrous material there can be a net reduction in $CO_2$ emissions [5].

Banana fiber is a naturally occurring biodegradable material obtained from shredding the discarded banana tree trunk. Due to the relatively high tensile strength of banana fibre it is commonly used in high-quality textiles, ropes, yarn, paper, composite and burlap [7]. The long banana fibers makes it attractive for use in forming slab-like flexible thermal insulation batt for building wall cavity insulation. However, for this purpose an in-depth analysis of the thermal insulating characteristics of the material is needed. In this study thermal conductivity measurements were undertaken on slab-like specimens of banana fiber and the results analyzed to develop empirical correlations to determine the thermal conductivity variation with density and mean temperature.

## 2. THERMAL CONDUCTIVITY EXPERIMENTAL RESULTS

Banana fibre test specimens were prepared by randomly arranging the banana fibres horizontally to form an insulation batt in square polystyrene frames of thickness 25.4 mm, 38 mm and 50.4 mm, respectively. Figure 1 shows a picture of the dried and sorted banana fibre.

FIGURE 1: DRIED AND SORTED BANANA FIBRE

The polystyrene frames were constructed from 25.4 mm strips with a thin plastic base to hold the fibres from falling through. The inner dimensions of the specimen holder was 254 mm x 254 mm. Test specimens were prepared at densities 20 $kg/m^3$, 30 $kg/m^3$, 40 $kg/m^3$, 50 $kg/m^3$, 60 $kg/m^3$, 70 $kg/m^3$, 80 $kg/m^3$, 90 $kg/m^3$, 100 $kg/m^3$, 110 $kg/m^3$ and 120 $kg/m^3$, at the respective thickness of 25.4 mm, 38 mm and 50.4 mm. The minimum test density was determined form the density at which the banana fibres settled under natural conditions. The maximum test density was determined by the clamping force of the test apparatus. The mass of fibre for the respective test specimens was calculated form the target density and the known specimen holder volume.

Thermal conductivity measurements were conducted using the LaserComp FOX 304 steady state thermal conductivity measurement apparatus which operated in accordance with ASTM C-518-04, Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus [8]. The FOX 304 measures thermal conductivity under steady state one-dimensional test conditions with heat flow upwards via a centrally located 102 mm X 102 mm heat flux transducer. 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 (Figure 2).

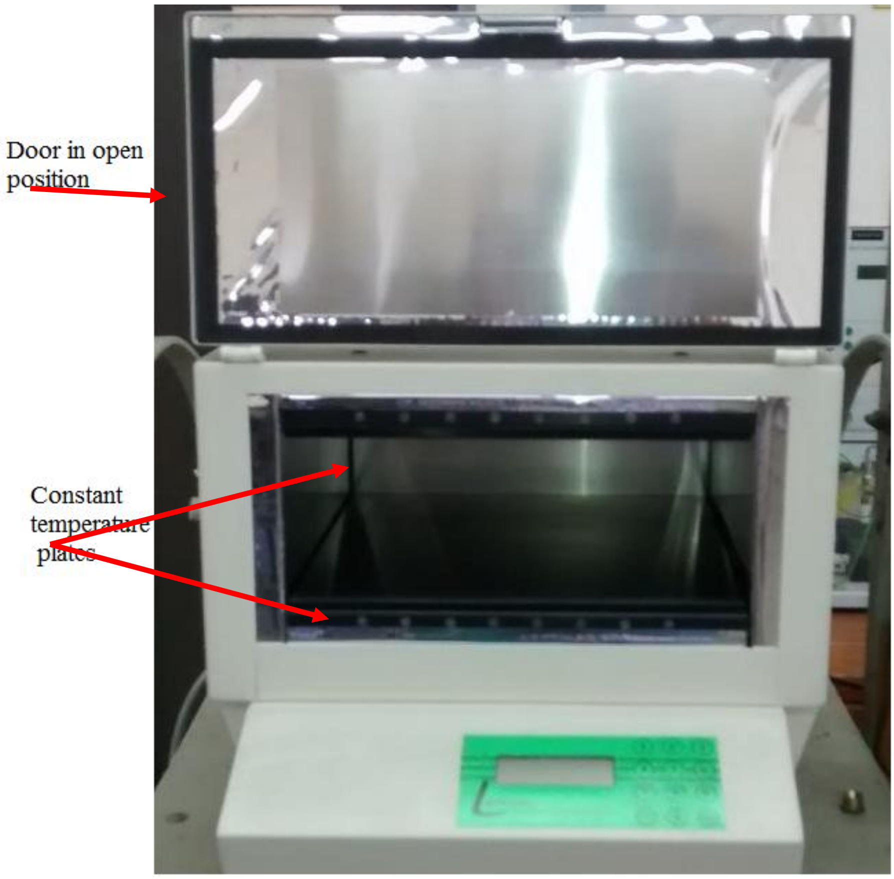


FIGURE 2: LASERCOMP FOX 304 IN OPEN POSITION

The machine 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 sink for the FOX 304 was provided by an independent chilled water system and a circulating pump. The test results for the 25.4 mm, 38 mm and 50.4 mm specimens are shown on Table 1, Table 2 and Table 3, respectively.

TABLE 1: BANANA FIBRE EXPERIMENTAL THERMAL CONDUCTIVITY TEST RESULTS - 25.4 MM THICK SPECIMEN

| **Density (kg/m$^3$)** | **Experimental Determined Thermal Conductivity (W/m.K) ± 0.2%** | | | | |
|---|---|---|---|---|---|
| | **20 ˚C** | **25 ˚C** | **30 ˚C** | **35 ˚C** | **40 ˚C** |
| 20 | 0.05397 | 0.05563 | 0.05729 | 0.05891 | 0.06079 |
| 30 | 0.04787 | 0.04917 | 0.05046 | 0.05176 | 0.05327 |
| 40 | 0.04310 | 0.04424 | 0.04541 | 0.04657 | 0.04777 |
| 50 | 0.04158 | 0.04258 | 0.04361 | 0.04456 | 0.04564 |

| | | | | | |
|---|---|---|---|---|---|
| 60 | 0.04001 | 0.04092 | 0.04186 | 0.04256 | 0.04355 |
| 70 | 0.03930 | 0.04020 | 0.04112 | 0.04195 | 0.04285 |
| 80 | 0.03880 | 0.03949 | 0.03998 | 0.04075 | 0.04172 |
| 90 | 0.03923 | 0.03996 | 0.04070 | 0.04166 | 0.04276 |
| 100 | 0.04013 | 0.04080 | 0.04137 | 0.04202 | 0.04282 |
| 110 | 0.04187 | 0.04219 | 0.04276 | 0.04324 | 0.04366 |
| 120 | 0.04421 | 0.04463 | 0.04532 | 0.04611 | 0.4754 |

TABLE 2: BANANA FIBRE EXPERIMENTAL THERMAL CONDUCTIVITY TEST RESULTS - 38 MM THICK SPECIMEN

| **Density ($kg/m^3$)** | **Experimental Determined Thermal Conductivity (W/m.K) ± 0.2%** | | | | |
|---|---|---|---|---|---|
| | **20 ˚C** | **25 ˚C** | **30 ˚C** | **35 ˚C** | **40 ˚C** |
| 20 | 0.06740 | 0.06934 | 0.07150 | 0.07380 | 0.07597 |
| 30 | 0.05251 | 0.05419 | 0.05594 | 0.05740 | 0.05926 |
| 40 | 0.04638 | 0.04770 | 0.04918 | 0.05070 | 0.05148 |
| 50 | 0.04290 | 0.04387 | 0.04501 | 0.04626 | 0.04655 |
| 60 | 0.04107 | 0.04197 | 0.04321 | 0.04454 | 0.04601 |
| 70 | 0.04063 | 0.04119 | 0.04196 | 0.04282 | 0.04408 |
| 80 | 0.04054 | 0.04110 | 0.04196 | 0.04281 | 0.04379 |
| 90 | 0.04093 | 0.04132 | 0.04260 | 0.04319 | 0.04427 |
| 100 | 0.04174 | 0.04176 | 0.04292 | 0.04395 | 0.04489 |
| 110 | 0.04268 | 0.04312 | 0.04409 | 0.04587 | 0.04621 |
| 120 | 0.04562 | 0.04629 | 0.04748 | 0.04924 | 0.05042 |

TABLE 3: BANANA FIBRE EXPERIMENTAL THERMAL CONDUCTIVITY TEST RESULTS – 50.4 MM THICK SPECIMEN

| **Density ($kg/m^3$)** | **Experimental Determined Thermal Conductivity (W/m.K) ± 0.2%** | | | | |
|---|---|---|---|---|---|
| | **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 |

## 3. ANALYSIS

The experimental results (Tables 1–3) for the loose-fill banana fibre specimens at the three thickness tested and 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 [5, 9, 10, 11]. 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) [5, 12].

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

where $\lambda$ is thermal conductivity in W/m.K, $\rho$ 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 (16).

For 25.4 mm thick specimen:-

At 20 ˚C mean temperature;

$$\lambda = 0.02294 + (0.12087 \times 10^{-3})\rho + 0.5926/\rho \qquad (2)$$

At 25 ˚C mean temperature;

$$\lambda = 0.02404 + (0.11418 \times 10^{-3})\rho + 0.6058/\rho \qquad (3)$$

At 30 ˚C mean temperature;

$$\lambda = 0.02478 + (0.11134 \times 10^{-3})\rho + 0.6258/\rho \qquad (4)$$

At 35 ˚C mean temperature;

$$\lambda = 0.02530 + (0.11095 \times 10^{-3})\rho + 0.6485/\rho \qquad (5)$$

At 40 ˚C mean temperature;

$$\lambda = 0.02549 + (0.11508 \text{ x } 10^{-3})\rho + 0.6816/\rho \quad (6)$$

For 38 mm thick specimen:-

At 20 ˚C mean temperature;

$$\lambda = 0.01214 + (0.19741 \text{ x } 10^{-3})\rho + 1.0309/\rho \quad (7)$$

At 25 ˚C mean temperature;

$$\lambda = 0.01264 + (0.19349 \text{ x } 10^{-3})\rho + 1.0642/\rho \quad (8)$$

At 30 ˚C mean temperature;

$$\lambda = 0.01276 + (0.19893 \text{ x } 10^{-3})\rho + 1.1046/\rho \quad (9)$$

At 35 ˚C mean temperature;

$$\lambda = 0.01185 + (0.21480 \text{ x } 10^{-3})\rho + 1.1640/\rho \quad (10)$$

At 40 ˚C mean temperature;

$$\lambda = 0.01163 + (0.22156 \text{ x } 10^{-3})\rho + 1.2094/\rho \quad (11)$$

For 50.4 mm thick specimen:-

At 20 ˚C mean temperature;

$$\lambda = 0.01587 + (0.19805 \text{ x } 10^{-3})\rho + 0.9468/\rho \quad (12)$$

At 25 ˚C mean temperature;

$$\lambda = 0.01646 + (0.19436 \text{ x } 10^{-3})\rho + 0.9798/\rho \quad (13)$$

At 30 ˚C mean temperature;

$$\lambda = 0.01740 + (0.19150 \text{ x } 10^{-3})\rho + 1.0079/\rho \quad (14)$$

At 35 ˚C mean temperature;

$$\lambda = 0.01401 + (0.22607 \text{ x } 10^{-3})\rho + 1.1186/\rho \quad (15)$$

At 40 ˚C mean temperature;

$$\lambda = 0.01615 + (0.20359 \text{ x } 10^{-3})\rho + 1.1154/\rho \quad (16)$$

Another characterise feature of loose-fill fibrous thermal insulation is an increase in thermal conductivity with mean test temperature [13]. The test results for banana fibre for all the density tested at the respective specimen thickness indicated a linear increase in thermal conductivity with mean test temperature. The $\lambda$ variation with mean test temperature can therefore be represented with a straight line equation of the form

$$\omega(T) = \mathrm{d} + \mathrm{e}.T \quad (17)$$

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 for determining λ in terms of temperature and specimen density for the banana fibre specimens as shown in equations (18) to (20). The respective thermal conductivity value was calculated form the empirical correlations for the experimental conditions reported and the percentage difference between the theoretical and experimental λ determined. The results are shown on tables 4 to 6.

The correlation for the 25.4 mm thick specimen;

$$\lambda = (0.0207 + 0.127 \text{ x } 10^{-3}\, T) + (0.1234 \text{ x } 10^{-3} - 0.2962^{-6}\, T)\rho + (0.4984 + 0.4414^{-2}\, T)/\rho \quad (18)$$

The correlation for the 38 mm thick specimen;

$$\lambda = (0.01329 - 0.3616 \text{ x } 10^{-4}\, T) + (0.1635 \text{ x } 10^{-3} - 0.1392^{-5}\, T)\rho + (0.8405 + 0.9137^{-2}\, T)/\rho \quad (19)$$

The correlation for the 50.4 mm thick specimen;

$$\lambda = (0.01712 - 0.381 \text{ x } 10^{-4}\, T) + (0.177 \text{ x } 10^{-3} + 0.8556^{-6}\, T)\, \rho + (0.7482 + 0.9518^{-2}\, T)/\rho \quad (20)$$

TABLE 4: PERCENTAGE DIFFERENCE BETWEEN THE CALCULATED EMPIRICAL CORRELATION THERMAL CONDUCTIVITY FROM EQUATION (18) AND THE EXPERIMENTAL RESULTS FROM TABLE 1 FOR 25.4MM THICK BANANA FIBRE SPECIMN

| **Density ($kg/m^3$)** | **Calculated Empirical Correlation Thermal Conductivity (W/m.K) - Equation (18) and % Difference from Experimental Thermal Conductivity – Table 1** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **20 ˚C** | | **25 ˚C** | | **30 ˚C** | | **35 ˚C** | | **40 ˚C** | |
| | $\lambda_{empirical}$ W/m.K | % Diff. | $\lambda_{empirical}$ W/m.K | % Diff. | $\lambda_{empirical}$ W/m.K | % Diff. | $\lambda_{empirical}$ W/m.K | % Diff. | $\lambda_{empirical}$ W/m.K | % Diff. |
| 20 | 0.05492 | 1.77 | 0.05663 | 1.80 | 0.05834 | 1.84 | 0.06005 | 1.94 | 0.06176 | 1.60 |
| 30 | 0.04632 | -3.24 | 0.04765 | -3.10 | 0.04897 | -2.95 | 0.05030 | -2.82 | 0.05163 | -3.09 |
| 40 | 0.04261 | -1.15 | 0.04373 | -1.15 | 0.04486 | - | 0.04599 | -1.25 | 0.04712 | -1.37 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | 1.21 | | | | |
| 50 | 0.04085 | -1.76 | 0.04185 | -1.72 | 0.04285 | -1.74 | 0.04385 | -1.59 | 0.04486 | -1.72 |
| 60 | 0.04007 | 0.14 | 0.04098 | 0.14 | 0.04189 | 0.08 | 0.04281 | 0.58 | 0.04372 | 0.39 |
| 70 | 0.03984 | 1.38 | 0.04069 | 1.22 | 0.04154 | 1.01 | 0.04238 | 1.03 | 0.04323 | 0.89 |
| 80 | 0.03997 | 3.01 | 0.04076 | 3.22 | 0.04155 | 3.94 | 0.04235 | 3.92 | 0.04314 | 3.40 |
| 90 | 0.04033 | 2.80 | 0.04108 | 2.79 | 0.04182 | 2.76 | 0.04257 | 2.18 | 0.04332 | 1.30 |
| 100 | 0.04085 | 1.80 | 0.04156 | 1.86 | 0.04227 | 2.17 | 0.04297 | 2.27 | 0.04368 | 2.01 |
| 110 | 0.04149 | -0.90 | 0.04217 | -0.06 | 0.04284 | 0.18 | 0.04351 | 0.63 | 0.04418 | 1.20 |
| 120 | 0.04222 | -4.50 | 0.04286 | -3.96 | 0.04351 | -4.00 | 0.04415 | -4.26 | 0.04479 | -5.79 |

TABLE 5: PERCENTAGE DIFFERENCE BETWEEN THE CALCULATED EMPIRICAL CORRELATION THERMAL CONDUCTIVITY FROM EQUATION (19) AND THE EXPERIMENTAL RESULTS FROM TABLE 2 FOR 38MM THICK BANANA FIBRE SPECIMN

| **Density (kg/m$^3$)** | **Calculated Empirical Correlation Thermal Conductivity (W/m.K) - Equation (19) and % Difference from Experimental Thermal Conductivity – Table 2** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **20 °C** | | **25 °C** | | **30 °C** | | **35 °C** | | **40 °C** | |
| | $\lambda_{empirical}$ W/m.K | % Diff. | $\lambda_{empirical}$ W/m.K | % Diff. | $\lambda_{empirical}$ W/m.K | % Diff. | $\lambda_{empirical}$ W/m.K | % Diff. | $\lambda_{empirical}$ W/m.K | % Diff. |
| 20 | 0.06756 | 0.23 | 0.06980 | 0.66 | 0.07204 | 0.76 | 0.07428 | 0.66 | 0.07653 | 0.73 |
| 30 | 0.05242 | -0.18 | 0.05397 | -0.41 | 0.05552 | -0.76 | 0.05707 | -0.58 | 0.05862 | -1.08 |
| 40 | 0.04580 | -1.25 | 0.04704 | -1.38 | 0.04828 | -1.83 | 0.04952 | -2.33 | 0.05076 | -1.40 |
| 50 | 0.04260 | -0.70 | 0.04368 | -0.44 | 0.04476 | -0.56 | 0.04584 | -0.91 | 0.04692 | 0.80 |
| 60 | 0.04110 | 0.07 | 0.04210 | 0.31 | 0.04310 | -0.26 | 0.04409 | -1.00 | 0.04509 | -1.99 |
| 70 | 0.04058 | -0.13 | 0.04154 | 0.84 | 0.04250 | 1.28 | 0.04345 | 1.48 | 0.04441 | 0.76 |
| 80 | 0.04066 | 0.30 | 0.04161 | 1.24 | 0.04256 | 1.42 | 0.04350 | 1.62 | 0.04445 | 1.51 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 90 | 0.04115 | 0.55 | 0.04211 | 1.91 | 0.04306 | 1.08 | 0.04401 | 1.91 | 0.04497 | 1.58 |
| 100 | 0.04193 | 0.46 | 0.04290 | 2.74 | 0.04388 | 2.23 | 0.04485 | 2.04 | 0.04582 | 2.07 |
| 110 | 0.04291 | 0.55 | 0.04391 | 1.84 | 0.04491 | 1.87 | 0.04591 | 0.10 | 0.04691 | 1.52 |
| 120 | 0.04405 | -3.44 | 0.04509 | -2.60 | 0.04612 | -2.86 | 0.04716 | -4.23 | 0.04819 | -4.42 |

TABLE 6: PERCENTAGE DIFFERENCE BETWEEN THE CALCULATED EMPIRICAL CORRELATION THERMAL CONDUCTIVITY FROM EQUATION (20) AND THE EXPERIMENTAL RESULTS FROM TABLE 3 FOR 50.4MM THICK BANANA FIBRE SPECIMN

| **Density ($kg/m^3$)** | **Calculated Empirical Correlation Thermal Conductivity (W/m.K) - Equation (20) and % Difference from Experimental Thermal Conductivity – Table 3** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **20 ˚C** | | **25 ˚C** | | **30 ˚C** | | **35 ˚C** | | **40 ˚C** | |
| | $\lambda_{empirical}$ W/m.K | % Diff. | $\lambda_{empirical}$ W/m.K | % Diff. | $\lambda_{empirical}$ W/m.K | % Diff. | $\lambda_{empirical}$ W/m.K | % Diff. | $\lambda_{empirical}$ W/m.K | % Diff. |
| 20 | 0.06717 | 0.57 | 0.06944 | 0.61 | 0.07172 | 0.51 | 0.07399 | 0.44 | 0.07627 | 1.24 |
| 30 | 0.05347 | 0.11 | 0.05499 | 0.00 | 0.05652 | -0.48 | 0.05804 | -0.87 | 0.05956 | 0.29 |
| 40 | 0.04759 | -1.19 | 0.04876 | -1.20 | 0.04993 | -2.02 | 0.05110 | -2.93 | 0.05227 | -3.12 |
| 50 | 0.04484 | -2.78 | 0.04581 | -1.99 | 0.04679 | -1.44 | 0.04776 | -1.52 | 0.04874 | -2.23 |
| 60 | 0.04365 | 0.23 | 0.04451 | 0.18 | 0.04537 | 0.37 | 0.04623 | 1.02 | 0.04709 | 0.68 |
| 70 | 0.04336 | 2.47 | 0.04415 | 0.51 | 0.04493 | -2.55 | 0.04572 | 0.12 | 0.04651 | 0.07 |
| 80 | 0.04362 | 3.81 | 0.04437 | 3.79 | 0.04512 | 1.70 | 0.04586 | 2.28 | 0.04661 | 3.69 |
| 90 | 0.04426 | 0.84 | 0.04498 | 0.72 | 0.04571 | 0.92 | 0.04643 | 1.09 | 0.04715 | 4.90 |
| 100 | 0.04516 | 0.44 | 0.04587 | 1.73 | 0.04659 | 1.87 | 0.04730 | 2.67 | 0.04801 | 6.15 |
| 110 | 0.04625 | -0.48 | 0.04696 | 0.62 | 0.04767 | 0.58 | 0.04839 | -0.01 | 0.04910 | -0.97 |
| 120 | 0.04748 | -2.19 | 0.04820 | -2.06 | 0.04892 | -2.42 | 0.04964 | -3.45 | 0.05036 | -4.05 |

## 4. DISCUSSION

The experimental data of banana fibre exhibited the characteristic behaviour of loose–fill fibrous thermal insulation of decreasing thermal conductivity with increasing density to a minimum value and then increasing thermal conductivity with further increase in density. The optimum density at which the experimental results indicated minimum thermal conductivity was within the range of 70 $kg/m^3$ to 90 $kg/m^3$. The minimum thermal conductivity valve was recorded at the 80 $kg/m^3$ test as experiments were conducted in increments of 10 $kg/m^3$ change in density. From the experimental data, banana fibre specimens also exhibited the characteristic feature of increasing thermal conductivity with increasing mean test temperature. Therefore, the thermal insulating properties of banana fibre slab-like specimens is in line with other bio-degradable thermal insulations such as coconut fibre, sugarcane fibre and oil palm fibre [1]. Also, the optimum thermal conductivity is within the range 0.02 W/m.K to 0.06 W/m.K which is normally used for building thermal insulation [5, 14]

The Method of Least Squares was used with the experimental data to develop empirical correlations for calculating the apparent thermal conductivity of banana fibre with variation in density and mean test temperature. The calculated thermal conductivity form the empirical correlations also indicated the characteristic trends of loose-fill fibrous thermal insulation. The empirical values showed a minimum thermal conductivity within the range 60 $kg/m^3$ to 80 $kg/m^3$. The calculated value at 70 $kg/m^3$ was minimum as the thermal conductivity was determined in increments of 10 $kg/m^3$ change in density to facilitate comparison with the experimental data.

The percentage difference between the calculated thermal conductivity using the empirical correlation and the respective experimental thermal conductivity was determined and tabulated on Tables 4 to 6. The experimental thermal conductivity fluctuated above and below the calculated value showing positive and negative percentage differences. This was expected for any experimental data set. The mean percentage difference for the 25.4 mm thick specimens at $20^oC$, $25^oC$, $30^oC$, $35^oC$ and $40^oC$ over the test density range 20 $kg/m^3$ to 120 $kg/m^3$ was -0.06%, +0.09%, +0.19%, +0.24%, and -0.11%, respectively, and the mean percentage difference over the 55 test points calculated as +0.07%. Similarly, the mean percentage difference over the 55 test points for the 38 mm and 50.4 mm thick specimens are 0.04% and 0.13%, respectively. This indicates that the empirical correlations developed was capable of predicting the trends and thermal conductivity variation of the banana fibre specimens within an average percentage difference of ±0.2% of the experimental values.

## 5. CONCLUSIONS

Loose-fill banana fibre material exhibited the characteristic behaviour associated with fibrous thermal insulation and thermal conductivity tests showed that at the optimum density (lowest thermal conductivity) banana fibre is within the range for use as building thermal insulation. The empirical correlations developed from the experimental results predicted the trends and behaviour of the banana fibre within an average percentage difference of ±0.2% of the experimental values. The empirical correlations can be used to calculate the thermal conductivity of the banana fibre specimens at any combination of mean test temperature and density within the range tested.

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