Biodegradable Fibrous Thermal Insulation

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This study investigates the potential of naturally occurring biodegradable fibers for use as building thermal insulation. The use of biodegradable building thermal insulation would alleviate the environmental problems presently associated with the disposal of currently used man-made non-biodegradable thermal insulations. The apparent thermal conductivity(λ) for biodegradable coconut and sugarcane fiber were investigated in accordance with ASTM C 518 over the density ranges 40 kg/m^3 to 90 kg/m^3 and 70 kg/m^3 to 120 kg/m^3 for the test temperature ranges 13.2^{o}C to 21.8^{o}C and 18^{o}C to 32^{o}C, respectively. The experimental data were used to determine empirical equations for λ variation with density and temperature for both coconut and sugarcane fiber. Comparison of λ at 24^{o}C for coconut and sugarcane fiber were made with seven different conventional insulation from published data. The results indicated that the minimum λ for both coconut and sugarcane fiber are within the range normally associated with building thermal insulation. The λ variation with density and mean temperature for both coconut and sugarcane fiber were consistent with the behavior of loose-fill thermal insulation.

***Keywords**: Fibrous insulation, building insulation, coconut fiber, sugarcane fiber*

Introduction

In recent years retrofitting, refurbishing, reconstructing and upgrading existing structures has seen a growing volume of discarded insulation for disposal. The man-made non-biodegradable materials are fast filling the landfills and becoming a problem for disposal. This is creating an environmental problem for developing countries which do not have the proper facilities to accommodate or recycle material. Factoring in the environmental issue has turned research towards finding biodegradable environmentally friendly insulation.

The aim of this research is to investigate the potential of indigenous biodegradable fibrous materials (coconut fiber and sugarcane fiber) for use as building thermal insulation. In most tropical developing countries, coconut and sugarcane fiber are by-products of the coconut and sugarcane industries and these materials usually go to waste.

Nomenclature

a = constant
b = constant
c = constant
d = constant
e = constants
T = Temperature, ^{o}C, K

Greek Symbols

λ *= apparent thermal conductivity, W/m.K*
$\omega(T)$ *= expression for temperature dependance*
ρ *= density, kg/m^3*

Biodegradable Thermal Insulation

The term biodegradable in this study refers to material that occur naturally in nature and when disposed off will decompose without causing any adverse effects on the environment. In this context by-products from the agricultural industry were considered. The waste material from the copra (coconut processing) industry showed a high degree of fibrous content. When shredded the resulting coconut fiber showed physical properties of fibers with a mean diameter of 0.267 mm with a range between 0.104 mm to 0.502 mm and a standard deviation of 9.04 x 10^{-2} (CARIRI project report, 1996). When arranged in a slab-like form as a thermal insulation batt the minimum density of coconut fiber without settling was 40 kg/m^3 (Kochhar and Manohar, 1997).

By products from the sugarcane industry were also looked at for use as thermal insulation. Sugarcane fiber (bagasse) consists of fibers of mean diameter 0.313 mm with a range between 0.156 mm to 0.504 mm and a standard deviation of 7.53 x 10^{-2} (CARIRI project report, 1996). When arranged in a slab-like form as a thermal insulation batt the minimum density of sugarcane fiber without settling was 70 kg/m^3 (Kochhar and Manohar, 1997).

Thermal Conductivity Measurement

The thermal insulating properties of coconut fiber and sugarcane fiber were measured in accordance with ASTM C518 where the apparent thermal conductivity, λ, were measured under steady-state one-dimensional test conditions with heat flow upwards (Kochhar and Manohar, 1997). The test equipment used constant temperature plate 305 mm x 305 mm with a centrally located 102 mm x 102 mm heat flux transducers. The test equipment provided λ measurements with ±0.2% repeatability and ±0.5% reproducibility within the range 0.005 W/m.K to 0.35 W/m.K (LaserComp FOX 304, 1994).

Thermal conductivity measurements were conducted on 52 mm thick, 254 mm square test specimens. The specimens were contained in a polystyrene specimen holder constructed from 25.4 mm thick polystyrene strips, 52 mm high. Coconut and sugarcane fiber samples were randomly selected from two respective stockpiles of air-dried material. The minimum test density for each material was determined by the lowest possible density for which the material existed under gravity without any appreciable settling. The clamping force between the constant temperature plates of the test equipment determined the upper test density limit.

For coconut fiber thermal conductivity tests were conducted at mean test temperatures of 15.6^{o}C with a temperature difference of 16.3^{o}C and 21.8^{o}C with a temperature difference of 13.2^{o}C. For these test conditions three tests were conducted on each specimen of density 40 kg/m^3, 50 kg/m^3, 60 kg/m^3, 70 kg/m^3, 80 kg/m^3, and 90 kg/m^3. The mean values of the experimental test results for coconut fiber are shown on Table 1.

For sugarcane fiber thermal conductivity tests were conducted at mean test temperatures of 18^{o}C, 24^{o}C and 32^{o}C with a temperature difference of 22^{o}C in each case. For these test conditions three tests were conducted on each specimen of density 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. The mean values of

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the experimental test results for sugarcane fiber are shown on Table 2.

Table 1. Experimentally determined λ for coconut fiber.

Density (Kg/m^3)	Experimental λ (W/m.K) ± 0.2%	
	15.6 ^{o}C	21.8 ^{o}C
40	0.05624	0.05758
50	0.05099	0.05184
60	0.05051	0.04970
70	0.04891	0.04884
80	0.04800	0.04886
90	0.04869	0.05009

Table 2. Experimentally determined λ for sugarcane fiber.

Density (Kg/m^3)	Experimental λ (W/m.K) ± 0.2%		
	18^{o}C	24^{o}C	32^{o}C
70	0.04977	0.05094	0.05314
80	0.04851	0.04966	0.05060
90	0.04851	0.04896	0.04947
100	0.04610	0.04680	0.04862
110	0.04909	0.04992	0.04963
120	0.04888	0.04964	0.05099

The experimental results for both coconut and sugarcane fibers indicated the general trend associated with loose-fill thermal insulation (Bankvall, 1973; Pratt, 1978). That is, as density increases from the minimum possible value upwards, λ decreases to a minimum and then increases. Therefore, the λ variation with density should satisfy the general empirical relationship associated with this characteristic behavior of materials of this nature as given in Eq.(1) (Bankvall, 1974).

$$\lambda = a + b\rho + c/\rho \tag{1}$$

Using the Method of Least Squares, the experimental data for coconut fiber and sugarcane fiber for each test condition were fitted in the form of Equation (1) and the empirical constants were determined. The resulting equations are as follows:

Coconut Fiber 15.6^{o}C mean test temperature;

$$\lambda = 0.19236 \text{ x } 10^{-1} + 0.18031 \text{ x } 10^{-3}\rho + 1.1812/\rho \tag{2}$$

Coconut Fiber 21.8^{o}C mean test temperature;

$$\lambda = -0.14291 \text{ x } 10^{-2} + 0.34979 \text{ x } 10^{-3}\rho + 1.1812/\rho \tag{3}$$

Sugarcane Fiber 18^{o}C mean test temperature;

$$\lambda = -0.21107 \text{ x } 10^{-2} + 0.26227 \text{ x } 10^{-3}\rho + 2.3580/\rho \tag{4}$$

Sugarcane Fiber 24^{o}C mean test temperature;

$$\lambda = -0.99910 \text{ x } 10^{-2} + 0.30485 \text{ x } 10^{-3}\rho + 2.7878/\rho \tag{5}$$

Sugarcane Fiber 32^{o}C mean test temperature;

$$\lambda = -0.31685 \text{ x } 10^{-1} + 0.41687 \text{ x } 10^{-3}\rho + 3.9030/\rho \tag{6}$$

Another characteristic feature of lose-fill insulation is an increase of λ with mean test temperature (Manohar, Yarbrough and Kochhar, 2000). In general, the experimental results for both coconut fiber and sugarcane fiber showed linearly increasing λ with temperature. In order to determine λ variation with mean test temperature, the respective coefficients of a, b, and c, from the isothermal equations for both coconut and sugarcane fiber were fitted to a relationship of the general form;

$$\omega(T) = d + e.T \tag{7}$$

where $\omega(T)$ is an expression for temperature dependance, d and e are constants, and T is the temperature. This resulted in general empirical relationships for determining λ in terms of temperature and specimen density for coconut and sugarcane fiber.

Coconut Fiber:

$$\lambda = (0.071232 - 0.003333T) + (-0.000246 + 2.73355 \text{ x } 10^{-5}T)\rho + (-0.372006 + 0.099565T)/\rho \tag{8}$$

Sugarcane Fiber:

$$\lambda = (0.38311 \text{ x}10^{-1} - 0.21448 \text{ x}10^{-2}\, T) + (0.51660 \text{ x } 10^{-4} + 0.11203 \text{ x}10^{-4}\, T)\rho + (0.25540 + 0.11193T)/\rho \tag{9}$$

Comparison of Thermal Conductivity Data

The general empirical relationships from equations (8) and (9) were used to calculate the apparent thermal conductivity for coconut and sugarcane fiber, respectively, at a mean test temperature of 24^{o}C. Thermal conductivity values were determined for the respective test densities and are given on Tables 3 and 4.

Table 3. Theoretical apparent thermal conductivity of coconut fiber at 24 ^{o}C from Eq. (8).

Density (kg/m^3)	Thermal Conductivity,λ (W/m.K)
40	0.05808
50	0.05209
60	0.04947
70	0.04877
80	0.04926
90	0.05056

This data was compared with published results for kapok, jute (Stephenson and Mark, 1961), glass fiber (Battacharyya, 1980), air-filled foam (Glicksman, 1994), molded polystyrene, cellulose, and rock wool (Tye et al., 1980). A graphical interpretation of the results is shown in Figure 1.

Table 4. Theoretical apparent thermal conductivity of sugarcane fiber at 24 ^{o}C from Eq. (9).

Density (kg/m^3)	Thermal Conductivity,λ (W/m.K)
70	0.05130
80	0.04925
90	0.04837
100	0.04831
110	0.04884
120	0.04981

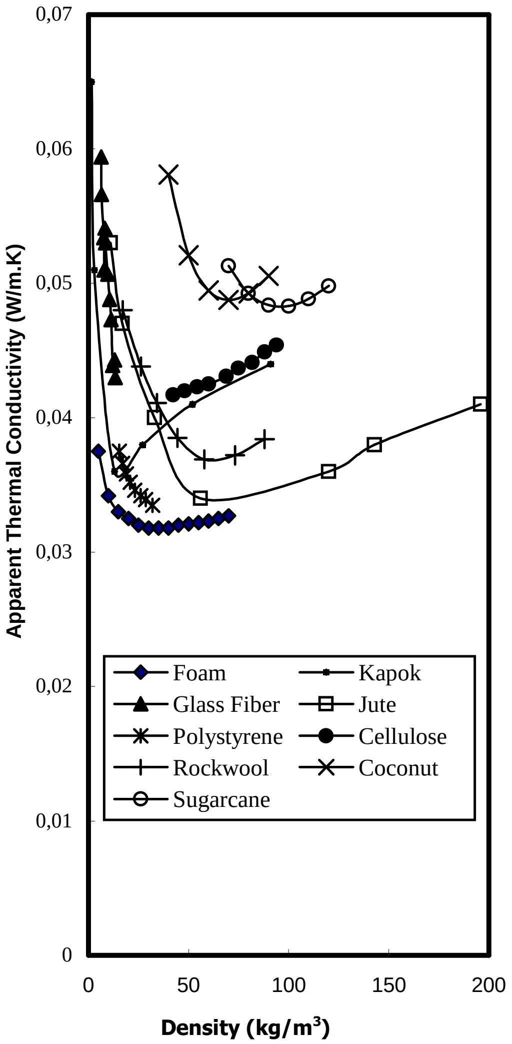

Figure 1. Comparative apparent thermal conductivity data for nine insulations.

Discussion

Experimental data at various mean test temperatures show the thermal conductivity variation with density for coconut fiber and sugarcane fiber followed the characteristic hooked shape associated with loose-fill fibrous insulation. The λ variation with density for coconut fiber showed the minimum λ value at a density of 80 kg/m^3 for experiments conducted at mean test temperatures of 15.6^{o}C and 21.8^{o}C. For sugarcane fiber the minimum λ value occurred at a density of 100 kg/m^3 for tests conducted at mean temperatures of 18^{o}C, 24^{o}C and 32^{o}C. For both material the minimum λ showed an increase with mean test temperature which is consistent with the behavior of loose-fill thermal insulation (Pratt, 1978). The empirical relationships for the λ variation with temperature and density for coconut and sugarcane fiber indicated behavior consistent with loose-fill insulating materials.

The minimum λ for coconut and sugarcane fiber ranged between 0.048 W/m.K to 0.049 W/m.K and 0.046 W/m.K to 0.049 W/m.K over the temperature ranges 15.6^{o}C to 21.8^{o}C and 18^{o}C to 32^{o}C, respectively. Comparison of the minimum λ of coconut and sugarcane fiber with different loose-fill materials from Figure 1 showed a λ difference ranging from 0.006 W/m.K with cellulose to 0.014 W/m.K with jute. Comparison of the minimum λ with the closed cell materials from Figure 1 showed a λ difference ranging from 0.014 W/m.K with molded polystyrene to 0.016 W/m.K with air-filled foam.

From the seven comparative insulation materials listed the percentage difference in λ ranged from 12.5% to 33% which indicated that coconut and sugarcane fiber are within the range of materials normally used for building thermal insulation.

These naturally occurring materials have the advantage of being environmentally friendly (biodegradable). However, consideration has to be given to the flammability of the materials and the higher density at which λ is minimum. Also, susceptibility to insect attack and fungal growth over long time periods need to be investigated.

Conclusions

Coconut fiber and sugarcane fiber have acceptable λ values for use as building thermal insulation.

The optimum λ values at 24^{o}C averaged about 0.0488 W/m.K and 0.0483 W/m.K for coconut and sugarcane fiber, respectively.

The λ of both coconut and sugarcane fiber increased with temperature within the test range of 15.6^{o}C to 32^{o}C. This behavior is consistent with loose fill insulating material.

Both coconut and sugarcane fiber exhibited the hooked shape graph of thermal conductivity with density. This behavior is consistent with loose fill insulating material.

Both materials have the advantage of being environmentally friendly (biodegradable).

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