COMPARATIVE STUDY OF THERMAL TRANSPORT IN ZEA MAYS STRAW AND ZEA MAYS HEARTWOOD (CORK) BOARDS

by

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Thermal conductivity values at the temperature of 301-303K have been measured for Zea mays straw board as well as Zea mays heartwood (cork) board. Comparative study of the thermal conductivity values of the boards reveal that Zea mays heartwood board has a lower thermal conductivity value to that of the straw board. The study also shows that the straw board is denser than the heartwood board. Specific heat capacity value is less in value for the heartwood board than the straw board. These parameters also affect the thermal diffusivity as well as thermal absorptivity values for the two types of boards. The result favours the two boards as thermal insulators for thermal envelop but with heartwood board as a preferred insulation material than the straw board.

Key words: *zea mays, straw board, heartwood, thermal insulation, thermal conductivity*

Introduction

Plant has been a useful source of raw material for production of material goods necessary for the existence, comfort, and conveniences of man. The list of such products include timber for structural designs and construction, alkaloids and other extracts for medical purposes and industrial use, manure for fertilization of soil, food for man and animal, and of course, fibre for thermal and acoustic insulation among others [1-5]

Beck *et al*. [6] have it that an interesting low-cost material readily available worldwide is straw from wheat, oats, barley, rice, or miscanthus. According to their report, in Germany millions of tons of straw could be utilized every year, for example, for roof insulation. Straw is steadily pressed to bales. Strawbale buildings were first constructed in the United States of America in the late 1800s following the advent of baling machines. Straw bales ceased to be used as a result of the introduction of cement which gained popularity in building industry over straw bale. The reports of Steen [7] and Nails [8] indicate that about 1000 new buildings are built annually worldwide, using straw due to increasing environmental awareness.

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According to Beck *et al*. [6], McCabe in 1993 measured the thermal conductivity of straw bales. His measurement revealed thermal conductivity λ values of about 0.054 W/mK for the heat flow perpendicular to the orientation of the straw, while thermal conductivity value of 0.061 W/mK was measured for the heat flow parallel to the orientation of the straw. This has also been reported in Commins [9]. The report of Anderson and Munch-Anderson, and Polin and Fleck as cited in Becks *et al*. [6] reveal 0.035-0.050 W/mK as the thermal conductivity of straw bale. This range of value is however in disparity and shows wide variation with the value 0.099 W/mK reported in Commins [9].

Zea mays is one of such plants. *Zea mays* is reported to be a native of America. It is commonly called maize, Indian corn or corn. Indian corn has been found in the tombs of the ancient Peruvians and in the mounds of the Aztecs. Columbus took samples of corn to Spain in 1502, and within a very short time, it spread over Southern Europe and Asia [10]. *Zea mays* is annual herb (grass) grown for the edible grains for food, production of starch, dextrin, syrup or sugar, whisky, beer, livestock feed, and for medicinal purposes [11]. The fine silk is for the treatment of bed-wetting and prostrate. It can grow to a height of 2.32 m and the stem could be up to 3 cm and above in diameter when it is cultivated in a fertile soil, but the stem or straw is not effectively put to use, if at all it is used.

The aim of this work is to investigate the thermophysical properties of maize heartwood (cork) board as well as that of the entire stem or straw board in order to assess their suitability as thermal envelope. In highly porous insulation materials such as fibre-boards, or pressed powder boards and foams, the total thermal conductivity λ can be expressed as the sum of the gaseous conductivity λ_{gas}, the solid conductivity λ_{solid}, radiative conductivity λ_{rad}, and a coupling term λ_{couple} [6, 12]:

$$\lambda = \lambda_{gas} + \lambda_{solid} + \lambda_{rad} + \lambda_{couple} \tag{1}$$

λ_{couple} accounts for the gas condition that thermally short circuits the high thermal resistance between the contact points between the fibres. According to Beck *et al*. [2], this contribution, is significant for insulation materials with a high conductivity as well as hindered heat flux in the porous solid structure, for example, from contact points, while conduction due to the gas contributes considerably to the thermal transport in insulation materials, solid conduction correlates directly and positively with density ρ. Moreso, the connectivity of the fibre is also a determining factor. It has been considered that the temperature dependence of the thermal conductivity of the bulk material is negligible in the temperature range $T = 0$ to 1000 °C.

Silva *et al*. [13] name thermal conductivity, specific heat capacity, and the thermal diffusivity as the major important properties of wood. They asserted that thermal diffusivity, as optical band energy, is important physical parameter to be considered in device modeling. Like the thermal diffusivity, the thermal conductivity is particularly an important parameter to manufacturing devices expressing the relationship between the parameters thus:

$$\lambda = D\rho C_p \tag{2}$$

where λ is the thermal conductivity, ρ – the density, D – the thermal diffusivity, and C_p – the specific heat capacity.

Sample preparation

The *Zea mays* investigated was grown in Uyo (5°2'N, 7°56'E) the capital of Akwa Ibom State in Nigeria. *Zea mays* is commonly and generally planted here in March and harvested for corn in between May and June. The straw is usually cut down and packed in heaps and left in the bush without any useful scientific or engineering purpose. It is at most burnt.

The maize straw was gotten fresh from the plantations where corn had been detached. The leaves were detached. The straw or stem were put into 10 different groups. Each group was subdivided into two groups, such that one sub-group had its outer layers peeled off to obtain the white corklike heartwood. The heartwood were chopped into small pieces and ground fresh using manual metallic grinder. The freshly ground heartwood was packed into a mould measuring 15.00 by 15.00 cm having a thickness of 1.15 cm and covered with a plane slab and compressed with mass of 15 kg. The setup was allowed to remain in that position for 48 hours before lifting the mass and kept in the sun for 5 days before removing it from the mould. The same procedure was repeated for the other nine samples. The ones so prepared were regarded as *Zea mays* stem and labelled from 1 to 10.

The other sets of sample in the sub-grouping was separately chopped into small pieces but with the hard brown outer layer not peeled. The grinding and moulding took the same procedure as the one described in *Zea mays* heartwood board. The samples were equally labelled.

The labelled samples in both cases were kept outside for sun drying in the day where there was sun and in the room in the night and whenever there was rain in the day.

The samples were left under the above condition for two years for complete dryness which was confirmed through regular measurement of mass of each sample to its constant mass. The samples were then shaped into the required sample specimen of 6.20 cm diameter with a thickness of 1.50 cm.

Experimental procedure

Thermal conductivity was determined using the steady-state method. A modified Lee's disc apparatus was used and the upper temperature as well as the lower temperature measured at steady-state when the heat conducted across the sample became equal to the rate at which it was emitted from the exposed surface. Thermal conductivity value was calculated using the modified Fourier equation expressed by several authors including Adeosun *et al.* [14] thus:

$$\lambda = \frac{MC_{\mathrm{p}}S_{\mathrm{C}}L}{A(T_1 - T_2)} \tag{3}$$

Dry samples were used to avoid the problem of moisture redistribution under the influence of a temperature gradient [15]. Walton [16] however reports that properly seasoned wood always contains a small amount of moisture, usually in the range of 8-16% of the oven dry weight of the wood material. This moisture content is rarely static, but tends to fluctuate with seasonal changes due to humid weather.

In order to obtain the small amount of moisture content of the seasoned dry samples investigated, the sample specimens already seasoned to dryness, to a constant mass as applicable to each sample, were subjected to method put forward by Walton. In the oven dry method, each sample used was first weighed using sensitive Mettler P165 weighing balance (Gallenhamp Product), then dried in an electric oven (FANEM) Model 315SE, at about 95 °C for 8 hours. The oven dried samples were immediately transferred to a desicator having completely charged silica gel, and allowed to be there for 24 hours in order to ensure complete removal of moisture. The same weighing balance was used to measure the mass of each of the samples as they were being removed from the desicator. The mass after seasoning and that of the oven dried, that is the new mass, were recorded from each sample accordingly.

Moisture content of the seasoned dry sample was determined using the measured mass after seasoning and the oven dried mass as expressed by Walton [16]. The heartwood board had a small percentage moisture content ranging between 8.13-8.33% of the oven dry while the straw boards had between 7.22-8.29%. The value here is within the range given by Walton [16], hence, acceptable for a properly seasoned wood. The samples used are therefore deemed dry or relatively dry with reference to fresh wet sample.

A well lagged calorimeter with sensitive thermometers were used for the determination of specific heat capacity C_p, of the sample specimens, employing cooling correction method to avoid heat loss through process of radiation [17].

Density ρ was also measured for the sample specimens using weighing and displacement method. The mass M of each sample was obtained by weighing using a sensitive electronics balance while the volume V was determined using the principle of Archimedes and calculated using the mathematical relation:

$$\rho \quad \frac{M}{V} \tag{4}$$

which abound in several books and journals including Ekpe *et al.* [18]. Measurement of displaced volume was taken immediately the sample was immersed to avoid soaking, which could lead to false measurement. The measured volume was compared with the ones obtained by direct calculations made based on the dimensional measurements, and the result were fairly the same. The average of the two was taken in each case for accuracy. Thermal diffusivity D was then calculated using the equation expressed by Liebe *et al*. [19] among others thus:

$$D \quad \frac{\lambda}{\rho C_{\mathrm{p}}} \tag{5}$$

Thermal absorbtivity α was then determined using the mathematical relationship:

$$\alpha \quad \sqrt{\frac{w}{2D}} \tag{6}$$

as expressed by authors including Khatry *et al*. [20] and Sodha *et al.* [21], where $w = 2\pi$/per period [s^{-1}].

Results and discussion

Tables 1 and 2 represent experimental investigation values for the *Zea mays* stem heartwood board and straw board, respectively. Comparatively, the heartwood or cork board with mean bulk density value of 192.17 ± 5.21 kg/m^3, has a mean thermal conductivity value of 0.0433 ± 0.0032 W/mK at temperature of 301-303 K which is far below that of *Zea mays* straw board, which is seen to be 0.0861 ± 0.0070 W/mK with mean bulk density value of 799.39 ± 27.37 kg/m^3.

Thermal conductivity value of *Zea mays* stem heartwood board is supportive of the values for cork reported by Diamant [22] as having density value of 180 kg/m^3 and thermal conductivity value of 0.046 W/mK with a specific heat capacity of 1758 J/kgK at a temperature

Table 1. Thermal properties of *Zea mays* stem heartwood (cork) board*

Sample code	Thermal conductivity, λ [$Wm^{-1}K^{-1}$]	Bulk density, ρ [kgm^{-3}]	Specific heat capacity, C_p [$Jkg^{-1}K^{-1}$]	Thermal diffusivity, D [$m^2s^{-1}\cdot10^{-7}$]	Thermal absorbtivity, α [m^{-1}]
1	0.0424 ± 0.0029	193.98 ± 5.52	1761.55 ± 17.10	1.201 ± 0.128	17.118 ± 0.912
2	0.0458 ± 0.0041	214.60 ± 7.17	1948.38 ± 18.98	1.095 ± 0.145	18.22 ± 1.206
3	0.0417 ± 0.0029	180.41 ± 4.10	1754.92 ± 16.64	1.317 ± 0.122	16.616 ± 0.767
4	0.0452 ± 0.0039	180.13 ± 5.56	1839.83 ± 17.43	1.364 ± 0.173	16.392 ± 1.038
5	0.0409 ± 0.0030	179.05 ± 3.82	1791.19 ± 17.38	1.275 ± 0.133	16.89 ± 0.882
6	0.0427 ± 0.0028	184.64 ± 4.02	2011.37 ± 18.31	1.150 ± 0.111	17.784 ± 0.880
7	0.0433 ± 0.0031	198.01 ± 5.16	2004.05 ± 18.61	1.091 ± 0.117	18.256 ± 0.976
8	0.0452 ± 0.0028	186.42 ± 4.21	1796.82 ± 17.30	1.269 ± 0.124	16.929 ± 0.830
9	0.0428 ± 0.0028	193.98 ± 5.49	1802.60 ± 18.66	1.224 ± 0.127	17.237 ± 0.894
10	0.0460 ± 0.0041	210.47 ± 6.98	1997.00 ± 20.01	1.094 ± 0.145	18.229 ± 1.208
Mean value ± error	0.0433 ± 0.0032	192.17 ± 5.21	1870.77 ± 18.02	1.208 ± 0.133	17.361 ± 0.959

* The measurements were made at 8.13-8.33% moisture content of the board

Table 2. Thermal properties of *Zea mays* straw board*

Sample code 1	Thermal conductivity, λ [$Wm^{-1}K^{-1}$]	Bulk density, ρ [kgm^{-3}]	Specific heat capacity, C_p [$Jkg^{-1}K^{-1}$]	Thermal diffusivity, D [m^2s^1]$\cdot10^{-8}$	Thermal absorbtivity, α [m^{-1}]
1	0.0859 ± 0.0070	801.71 ± 26.52	1852.741 ± 17.569	5.7830 ± 0.7173	25.0764 ± 1.555
2	0.0828 ± 0.0067	793.64 ± 26.17	2031.801 ± 19.039	5.1348 ± 0.6329	26.6124 ± 1.6401
3	0.0902 ± 0.0076	811.07 ± 29.39	1924.914 ± 18.273	5.7775 ± 0.7509	25.0886 ± 1.6304
4	0.0797 ± 0.0061	759.93 ± 24.96	1966.338 ± 18.474	5.3337 ± 0.6335	26.1116 ± 1.5507
5	0.0862 ± 0.0070	800.60 ± 26.36	1858.892 ± 17.590	5.7921 ± 0.7159	25.0569 ± 1.5485
6	0.0850 ± 0.0070	806.37 ± 27.06	1968.511 ± 20.457	5.3548 ± 0.6763	26.0599 ± 1.6457
7	0.0916 ± 0.0079	817.42 ± 29.74	2046.183 ± 20.893	5.4765 ± 0.7275	25.7687 ± 1.7115
8	0.0933 ± 0.0081	840.02 ± 32.22	2032.096 ± 20.744	5.4657 ± 0.7399	25.7942 ± 1.7460
9	0.0781 ± 0.0057	753.89 ± 24.11	2011.646 ± 20.492	5.1498 ± 0.5930	26.5736 ± 1.5299
10	0.0878 ± 0.0073	809.25 ± 27.17	2097.040 ± 21.016	5.1737 ± 0.6557	26.5121 ± 1.6801
Mean value ± error	0.0861 ± 0.0070	799.39 ± 27.37	1979.016 ± 19.455	5.4442 ± 0.6843	25.8654 ± 1.6248

* The measurements were made at 7.22-8.29% moisture content of the board

293-303 K. Thermal conductivity value for the *Zea mays* straw board as investigated falls within the range given by Commins [9] as 0.038-0.099 W/mK, the wide variation in bulk density value of the heartwood board with that of the entire straw board suggests the presence of large percentage of still air or dead air cell in the heartwood board cavity than the straw board, a situation that contributes to the wide disparity in thermal conductivity values of the two material samples.

Thermal conductivity has been described by Kimani *et al*. [23] as paramount of particular importance for selection of materials for thermal insulation. Thermal conductivity is a function of thermal diffusivity as expressed in eq. (2).

The later thermophysical parameter which also depend to a large extent on the density as well as, the specific heat capacity of the material has been found to be of less value for the straw board with a mean value of $(5.444 \pm 0.6843)\cdot 10^{-8}$ m^2/s than the stem heartwood board which has $(1.208 \pm 0.133)\cdot 10^{-7}$ m^2/s. This affects the thermal absorptivity value which has inverse relationship with the thermal diffusivity. Thermal absorptivity is high in value for straw board as compared with that of the stem heartwood. This is an indication that the heartwood board which is seen to have less absorptivity would also exhibit less emissivity following the postulation that emissivity is always equal to absorbtivity α at any given temperature [22].

Conclusions

Thermophysical properties of *Zea mays* stem heartwood and *Zea mays* straw boards have been investigated. Comparatively, the stem heartwood board possesses thermophysical properties in the range of those of already known good thermal insulating materials used for thermal envelope. Such materials include cork, with thermal conductivity value of 0.046 W/mK, bulk density of 180 kg/m^3 and specific heat capacity of 1758 J/kgK [22]. The result reveals low thermophysical property values for the heartwood board as compared to the straw board investigated. The values for the straw board are within the range of values for cardboard. The results indicates that the two types of boards produced from *Zea may*s plant have the potential for thermal insulation, but with *Zea mays* stem heartwood board exhibiting values for a better thermal insulation than the entire stem (straw) board. The heartwood board is therefore a preferred insulating material to the straw board. Hence, a suitable alternative to already and commonly used insulation materials that might be costly and scarce due to extensive usage.

Recommendation

It is expedient therefore, having compared the thermophysical properties of *Zea mays* stem heartwood board with those of the straw board, to recommend that *Zea mays* heartwood is a very useful raw material for production of insulation panel for use as thermal envelope especially now that other sources of already known insulation are becoming expensive and scarce due to high demand and extensive usage.

The research therefore provides a database for thermal properties of mature and harvested *Zea mays* stem and its heartwood as a source of insulation for thermal envelope.

Those in the building and other industries that have to do with thermal envelope production and utilization are encouraged to patronize this source of raw material for thermal insulation production.

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Nomenclature

A – area of sample, [m^2]
C_p – specific heat capacity of the material slab
D – thermal diffusivity, [m^{2}s^{-1}]
L – thickness of sample, [m]
M – mass, [kg]
S_C – gradient from cooling curves
T_1 – upper steady-state temperature, [K]
T_2 – lower steady-state temperature, [K]
V – volume, [m^3]

Greek letters

α – thermal absorbtivity, [m^{-1}]
λ – thermal conductivity, [Wm^{-1}K^{-1}]
ρ – density, [kgm^{-3}]

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