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Thermal conductivity, resistance and specific heat capacity of chemically-treated, widely-used timber for building-envelope

Charles Antwi-Boasiako* and Boakye K. Boadu

Department of Wood Science and Technology, Faculty of Renewable Natural Resources, Kwame Nkrumah University of Science and Technology, Kumasi-Ghana

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Wood has low thermal conductivity with high thermal resistance and specific heat capacity (SHC). Timber-designed building-envelopes have much resistance to solar radiation, which discomforts occupants. How chemicals alter thermal properties of preservative-treated non-durable woods for housing is inadequately studied. Two preservative-chemicals (*Erythropleum suaveolens* bark extract and inorganic Maneb/Lambda) influence on the SHC (determined by "method of mixtures") and, thermal conductivity and resistance (using Lee's Disc Apparatus) of *Ceiba pentandra* (a non-durable building timber) was investigated. Stakes treated with *E. suaveolens* and Maneb/Lambda recorded greater conductivity [$(0.005 \pm 0.001) \times 10^{-3}$ and $(0.006 \pm 0.0006) \times 10^{-3}$ W/m.K respectively] than *C. pentandra* control [$(0.004 \pm 0.0008) \times 10^{-3}$ W/m.K]. Conductivity was greater in longitudinal surface than radial and tangential directions for all stakes. Thermal resistance of stakes rated as: control [$(0.12 \pm 0.0008) \times 10^2 - (1.02 \pm 0.02) \times 10^2$ m^2K/W] > *E. suaveolens* [$(0.1 \pm 0.002) \times 10^2 - (0.76 \pm 0.02) \times 10^2$ m^2K/W] > Maneb/Lambda [$(0.1 \pm 0.002) \times 10^2 - (0.73 \pm 0.02) \times 10^2$ m^2K/W].

Maneb/Lambda-treated stakes obtained the greatest SHC [$(6810.9 \pm 12) \times 10^6$], then *E. suaveolens*-treated samples [$(5242.1 \pm 269.9) \times 10^6$] and untreated/control [$(4014.2 \pm 47.8) \times 10^6$]. Compared to other building materials (e.g., steel, aluminium and concrete), treated stakes have low thermal conductivity, with high thermal resistance and SHC, which is desired as an insulation material. Thus, while chemically-treated timber durability is

* Corresponding author: cantwiboasiako@gmail.com; c.antwiboasiako@yahoo.co.uk

improved, its insulating capacity to provide thermal comfort in buildings is assured.

Keywords: Heat transmission, organic preservative, specific heat capacity, steady-state, thermal insulation, wood anisotropy.

1 INTRODUCTION

Wood is one of the most indispensable building materials [1–4]. It is porous; it has low thermal conductivity, high resistance and specific heat capacity, which are important in designing a building-envelope with great resistance to heat flow [5–12]. At 12% moisture content (mc), the conductivity of structural softwood lumber is between 0.1 to 1.4 *w/m. K* as compared with those for structural materials such as aluminium (216 *w/m. K*), steel (45 *w/m. K*), concrete (0.9 *w/m. K*) and other materials including glass (1 *w/m. K*) and plaster (0.7 *w/m. K*) [13, 10]. Even materials for roofing, walling and panelling such as PolyVinyl Chloride (PVC) and asbestos have greater conductivity values (0.19 *w/m. K* and 0.14 *w/m. K* respectively) than that for wood (0.1 *w/m. K*) [10]. The implication is that, besides timber, most construction materials have greater ability to conduct heat from solar radiation and other sources into the interior spaces of buildings to cause more discomfort than wooden buildings during the warm spring and summer months or in tropical environments [14–16]. Such indoor discomfort, resulting from conductivity and specific heat capacity of materials other than the wood for making doors and roofing support, is undesirable [13, 17–21]. Thus, ceiling and other building materials may differ in their abilities to provide thermal insulation due to variations in their thermal properties. Specific heat capacity for untreated wood ranges between 1100–2510 $J.kg^{-1} k^{-1}$ [22–24]. However, that for treated wood, especially for tropical timbers, has not been established.

The insufficient supply of naturally-durable wood necessitates the use of non-durable species, which are supplementally protected with chemicals [25–27]. Conventional chemicals notably used to treat and preserve wood from wood-destroying insects, microbial and all forms of damage are presently of major concern to life [28]. [29] and [30] asserted that considerable efforts have been on-going in search of alternative chemicals that would not only match the efficacy of most valued traditional wood preservatives but, at the same time, possess reduced toxicity to the environment, generally cost-effective and with no damage to wood. This has increased the need for chemicals extracted from organic sources (i.e., plants and animals) [31–32]. Nevertheless, [33] reported that all forms of treatment affect wood properties. A reduction in mechanical properties such as toughness and tensile strength for wood treated with preservative-chemicals has been reported by [34–36]. In much the same way, the application of such chemicals to wood would be expected to affect its thermal properties (including conductivity, resistance and specific heat capacity). This paper sought to investigate the influence of water-borne preservatives (i.e., from organic and conventional inorganic sources) on the specific heat capacity, thermal conductivity and resistance of the preservative-treated stakes of *Ceiba pentandra* (L.) Gaertn., a non–durable timber employed for ceiling, walling and panelling of buildings to provide thermal comfort [37–39].

2 MATERIALS AND METHODS

2.1 Preparation of organic and inorganic preservative-chemicals for impregnation

The barks of two *E. suaveolens* trees were collected at their bases, which was 1 m above diameter at breast height, from the Botanical Garden of Kwame Nkrumah University of Science and Technology (KNUST), Kumasi-Ghana. The samples were washed thoroughly, cut into small chips, air-dried to 14% mc and milled to powder using a 40–60 mesh. 100 g of the powder was added to 1000 ml of distilled water and heated on water bath to 80 °C for 6 h with frequent stirring to avoid lumps. The solution was cooled, sieved with a 0.5 mm mesh and centrifuged (1600 $\times$ g for 1 h) to obtain the supernatant aqueous bark extract. Its concentration was determined after the aliquot (10 ml) in the Petri dish of a known mass was oven-dried at 105 $\pm$ 2 °C [40]. The concentration of the stock solution was then standardized at 1.5% using the serial dilution formula, $C1 \times V1 = C2 \times V2$, by [41] and [42]. A 2.5% stock solution of Lambda-cyhalothrin, an inorganic pesticide, was similarly standardized at 1.5%. 7.5 g of a fungicide, Maneb 80WP, was mixed with 500 ml of distilled water to obtain 1.5% [40]. 1.5% Maneb/Lambda mixture with pesticidal and fungicidal properties was obtained from 1.5% Lambda-cyhalothrin and 1.5% Maneb 80WP [1:1v/v] [43].

2.2 Determination of thermal conductivity and resistance

Thermal properties of *C. pentandra* were determined under room temperature, which is 25°C, at Thermal Department of Physics Laboratories, KNUST. Discs were cut to the same diameter (120 mm) and thickness (4 mm) as the brass plates of the Lee's Disc Apparatus [44–46] from defect–free *C. pentandra* samples and air-dried to 12% mc. Ninety discs were prepared and grouped into three (3) sets of 30 based on the grain directions of the timber: longitudinal (L), tangential (T) and radial (R) surfaces. Ten discs from each group were treated with *E. suaveolens* extract and another set with Maneb-Lambda at 124°C all under a pressure of 120 k Pa for 4 h. Ten untreated discs served as the control. The masses for the treated discs before and after impregnation

FIGURE 1
Thermal conductivity test with the Lee's disk apparatus. a - Tube connecting steam chest to brass base; b - Brass base; d - Brass disc; e - Thermometer measuring temperature of brass disc; f - Brass disc temperature; g - Brass base temperature; h - Bunsen burner; s - Steam chest; k - Temperature recorder.

were taken to determine their preservative-chemical retention. The cross sectional area (A) of the wood disc $\left(A = \frac{\pi d^2}{4}\right)$ was determined using their diameters (d). The steady-state method of determining thermal conductivity at 25 ºC was employed using the Lee's Disk Apparatus [44–50]. The Apparatus was assembled in accordance with its schematic operational illustration (Figures 1 and 2).

Each disc was sandwiched between the brass disc (D) and base (B) of the steam chest. Grease was smeared at both surfaces of the disc to ensure firm contact of B and D with the wood disc. Steam was passed through the steam chest to heat up the brass base, which was conducted across the disc. Temperatures of the brass base (T_2) and brass disc (T_1) were noted when a steady-state was reached (T_2 and T_1 changed by less than 0.5°C in 1 min.). The rate of heat conduction (H) across the wood sample at the steady-state equaled the rate of heat transmission from the wood or the exposed surface of the brass disc to the surrounding (Figure 3). To reduce losses to the barest minimum, each sample was a thin disc with a large cross-sectional area (A) $\left(A = \frac{\pi d^2}{4}\right)$ compared to the area exposed at the edge. At the steady-state, the rate of heat transfer (H) across the wood by conduction was given as in Eq. (1) [47–48, 50]:

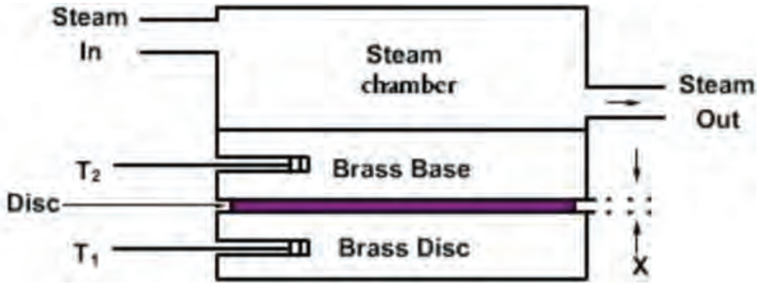

FIGURE 2
Schematic illustration of Lee's Disc Apparatus showing the position of the wood disc . T_1 - Temperature of brass disc at steady-state; T_2 - Temperature of brass base at steady-state; x - Thickness of wood disc [44].

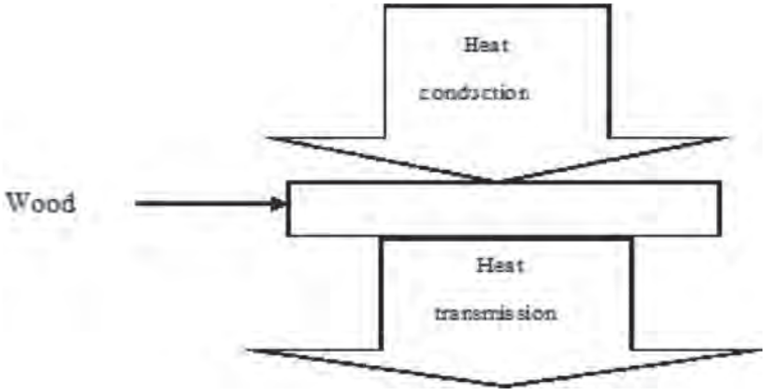

FIGURE 3
Illustration of heat conduction into and transmission from wood sample at steady-state.

$$H = kA * ((T_2 - T_1) / x) \tag{1}$$

Where: k = Thermal conductivity of the sample (W m^{-1} K^{-1}); A = Cross sectional area (m^2); $T_2 - T_1$(°C) = Temperature difference across wood sample; x = Wood thickness (m).

In much the same way, the rate of heat transfer or loss (H) from the wood (or brass disc to the environment) at steady-state was given in Eq. (2) [47, 48, 50]:

$$H = mc * dT / dt \tag{2}$$

Where: m = Mass of the brass disc (Kg); c = Specific heat capacity of brass ($JKg^{-1}K^{-1}$); H = Rate of heat loss; dT = Change in temperature as the disc cooled; dt = Time difference for the change in temperature as the disc cooled.

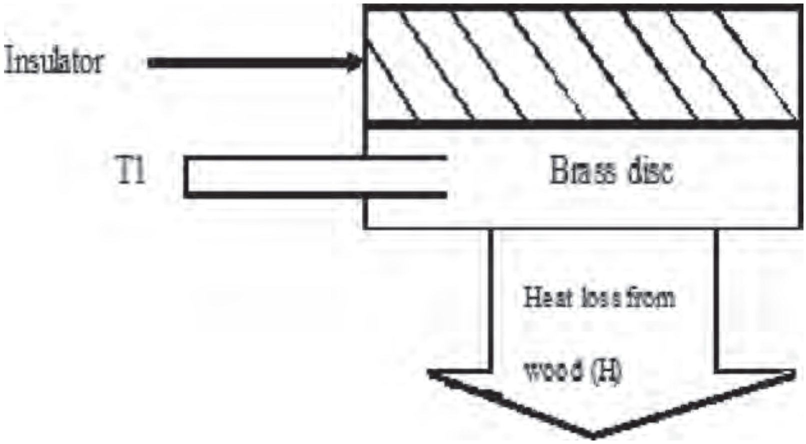

FIGURE 4
Insulated brass disc for the measurement of the rate of heat loss (cooling) (Source: [44]).

In calculating $\frac{dT}{dt}$, how fast the brass disc cooled at the previous (steady-state) temperature (T_1), the top of the brass disc was covered with an insulator (wood disc) (Figure 4).

The Lee's Apparatus was dismantled and the brass disc heated directly with the steam chamber. When the temperature of the brass disc was steady (i.e., as T_1 changed by less than 0.5°C in 1 minute), the steam chamber was removed and an insulator placed on top of the brass disc. The temperature of the brass disc was recorded every 30 sec. until 5°C below the previous (steady-state) value of T_1. The temperature and time were used to plot a cooling curve of Figure 5 [44].

The slope of the curve was given as *dT/dt*. If the rate of heat transfer across the wood sample (Eq. 2) at the steady-state was given as the rate at which heat was lost from the wood (Eq. 3), equating Eq. (1) to Eq. (2) gave Eq. (3) as follows:

$$kA * \left(\frac{T_2 - T_1}{x}\right) = mc * (dT / dt) \tag{3}$$

Knowing the mass (m) of the brass disc (kg), specific heat capacity of brass (c), change in temperature over time $\left(\frac{dT}{dt}\right)$, temperature of the brass base (T_2) and brass disc (T_1) at steady-state, the cross sectional area of the wood sample (A) and wood thickness (x), the thermal conductivity (k) was calculated from Eq. (3).

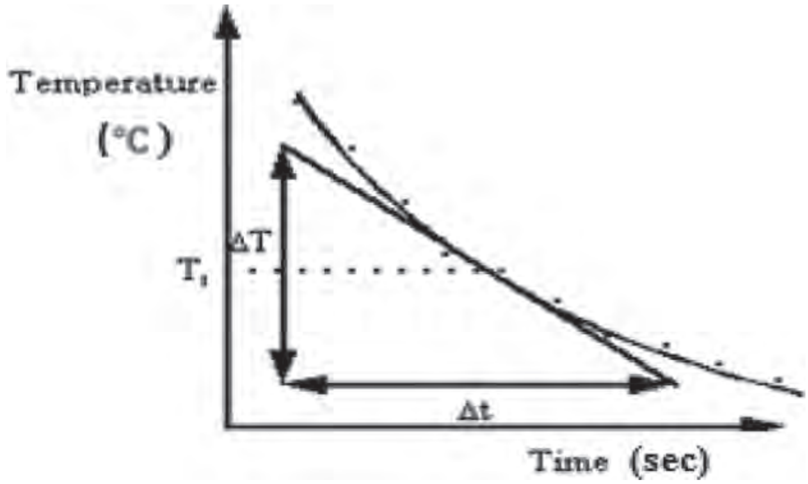

FIGURE 5
A curve showing the rate of cooling of the brass disc (Source: [44]).

The thermal conductivity values obtained and the thickness of the wood discs were used to determine the thermal resistance of treated and control stakes [48]:

$$R = \frac{x}{k} \tag{4}$$

Where: R = thermal resistance (m^2K/W); x = wood thickness (m); k = thermal conductivity.

2.3 Determination of specific heat capacity

A clay of known specific heat capacity (C_c) of 1381 J, $kg^{-1}\,k^{-1}$, given by [51], was moulded into a cylinder, 10 cm high and 1 cm in diameter, around a coiled wire, which emerged at both ends. Twenty-seven *C. pentandra* cylindrical samples, which were 10 cm high and 5 cm in diameter, nine (9) from each anisotropic direction (i.e., radial, longitudinal and tangential) were made. Two (2) holes with diameters of 1 cm and 0.5 cm were made vertically in them to accommodate the moulded clay and a thermometer, respectively (Figure 6).

Nine (9) samples (three from each direction) were pressure-impregnated with *E. suaveolens* extracts and other set with Maneb/Lambda mixture; nine (9) untreated samples served as the controls. Each wood sample was placed in a white refractory material to reduce heat loss to the surrounding (Figure 7).

The operational principles conformed to those underlying the traditional method of mixtures used in determining specific heat capacity of materials [14, 52]. The clay was heated by connecting probes from the Griffin Voltline

FIGURE 6
C. pentandra cylindrical samples for Specific Heat Capacity test: A (Treated with *E. suaveolens*), B (Control/untreated), C (Treated with Maneb-Lambda).

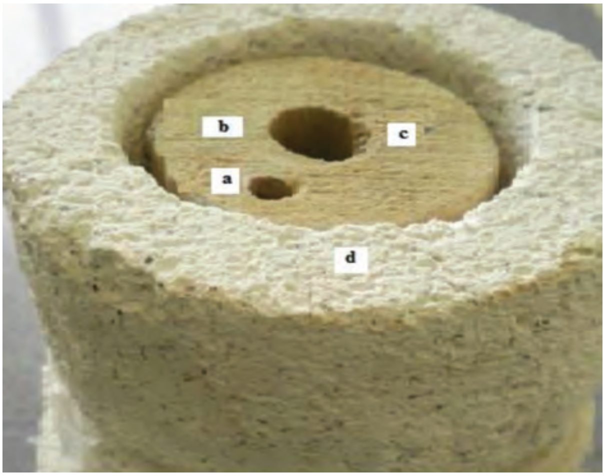

FIGURE 7
Wood sample displayed in a white refractory material (a – Small hole for thermometer; b – Wood Sample; c – Large hole to accommodate clay; d – White refractory material).

power supply to the wire at both ends [53]. The hot clay was quickly transferred into the larger hole in the wood; the temperature of the clay was recorded as its initial (Ti_c). Once in the wood, any heat loss by the clay was taken by the wood. The clay and wood temperatures were monitored to a point where the temperature of the wood, instead of increasing, began to fall. The highest temperature attained by the wood before the fall was recorded together with the corresponding temperature of the clay as Te_w and Te_c, respectively. According to [52], heat energy lost by the clay (Q) was mathematically determined (Eq. 5):

$$Q = M_c \times C_c \times (Ti_c - Te_c) \tag{5}$$

Where Q = Heat energy lost by clay; M_c = Mass of clay (kg); Ti_c = Initial temperature of clay (°C); Te_c = Final temperature of clay (°C); C_C = Specific Heat Capacity of clay (i. e., 1381 j. $kg^{-1} k^{-1}$).

Similarly, heat gained by the wood was represented mathematically (Eq. 6);

$$Q_1 = M_w \times C_w \times (Ti_w - Te_w) \tag{6}$$

Where; Q_1 = Heat gained by wood; M_w = Mass of wood (kg); C_w = Specific Heat Capacity of wood (J. $kg^{-1} k^{-1}$); Ti_w = Initial temperature of wood (°C); Te_w = Final temperature of wood (°C).

The assumption was that all the heat lost by the clay was given to the wood, which meant that the heat lost by the clay was equal to the amount gained. Therefore, $Q = Q_1$:

$$M_c \times C_c \times (Ti_c - Te_c) = M_w \times C_w \times (Ti_w - Te_w) \tag{7}$$

The specific heat capacity (C_w) of wood was accordingly determined:

$$C_w = ((M_c * C_c) * (Ti_c - Te_c)) / (M_w * (Ti_w - Te_w)) \tag{8}$$

2.4 Uncertainty Analysis

The rule for the propagation of fractional uncertainties by [54] was employed to determine the absolute uncertainty or error in the calculated values for thermal conductivity, resistance and specific heat capacity. The corrected values for the thermal properties were then obtained.

2.4.1 Thermal Conductivity

The corrected thermal conductivity of the wood samples was derived from Eq. (9):

$$K = K_1 \pm \Delta K_1 \tag{9}$$

Where: K = corrected thermal conductivity; K_1 = calculated thermal conductivity = $\left(\dfrac{mcx}{AT_2 - AT_1}\right) \times \left(\dfrac{dT}{dt}\right)$; ΔK_1 = error or uncertainty in the calculated thermal conductivity.

The uncertainty in the calculated thermal conductivity was determined from Eq. (10):

$$\frac{\Delta K_1}{K_1} = \sqrt{\left(\left(\frac{\Delta\left(\frac{(mcx)}{AT_2 - AT_1}\right)}{\left(\frac{(mcx)}{AT_2 - AT_1}\right)}\right)^2 + \left(\frac{\Delta\left(\frac{dT}{dt}\right)}{\left(\frac{dT}{dt}\right)}\right)^2\right)} \tag{10}$$

Where: $\Delta\left(\frac{mcx}{AT_2 - AT_1}\right)$ is the error in the $\left(\frac{mcx}{AT_2 - AT_1}\right)$ term of the thermal conductivity equation; $\Delta\left(\frac{dT}{dt}\right)$ = error in the $\left(\frac{dT}{dt}\right)$ term of the thermal conductivity equation.

$$\Delta K_1 = K_1\sqrt{\left(\left(\frac{\Delta\left(\frac{(mcx)}{AT_2 - AT_1}\right)}{\left(\frac{(mcx)}{AT_2 - AT_1}\right)}\right)^2 + \left(\frac{\Delta\left(\frac{dT}{dt}\right)}{\left(\frac{dT}{dt}\right)}\right)^2\right)} \tag{11}$$

Thus, from $K = K_1 \pm \Delta K_1$,

$$K = K_1 \pm \left(K_1\sqrt{\left(\left(\frac{\Delta\left(\frac{(mcx)}{AT_2 - AT_1}\right)}{\left(\frac{(mcx)}{AT_2 - AT_1}\right)}\right)^2 + \left(\frac{\Delta\left(\frac{dT}{dt}\right)}{\left(\frac{dT}{dt}\right)}\right)^2\right)}\right) \tag{12}$$

2.4.2 Thermal resistance

The corrected thermal resistance was obtained from Eq. (13):

$$R = R_1 \pm \Delta R_1 \tag{13}$$

Where: R = corrected thermal resistance; R_1 = calculated thermal resistance = $\frac{x}{k}$; ΔR_1 = error in the calculated thermal resistance.

The error in the calculated thermal resistance was determined (Eq. 14):

$$\frac{\Delta R_1}{R_1} = \sqrt{\left(\left(\frac{\Delta(x)}{x}\right)^2 + \left(\frac{\Delta k}{k}\right)^2\right)} \tag{14}$$

Where: $\Delta(x)$ is the error in the x term of the thermal resistance equation; Δk = error in the k term of the thermal resistance equation.

$$\Delta R_1 = R_1\sqrt{\left(\left(\frac{\Delta(x)}{x}\right)^2 + \left(\frac{\Delta k}{k}\right)^2\right)} \tag{15}$$

Thus, from $R = R_1 \pm \Delta R_1$,

$$R = R_1 \pm R_1\sqrt{\left(\left(\frac{\Delta(x)}{x}\right)^2 + \left(\frac{\Delta k}{k}\right)^2\right)} \tag{16}$$

2.4.3 Specific Heat capacity

For specific heat capacity, its corrected value was derived from Eq. (17):

$$C_w = C_{w1} \pm \Delta C_{w1} \tag{17}$$

Where: C_w = corrected specific heat capacity; C_{w1} = calculated specific heat capacity = $\left(\frac{M_c C_c}{M_w}\right)\times\left(\frac{Ti_c - Te_c}{Ti_w - Te_w}\right)$; ΔC_{W1} = error or uncertainty in the calculated specific heat capacity.

The uncertainty in the calculated specific heat capacity was determined from Eq. (18):

$$\frac{\Delta C_{w1}}{C_{w1}} = \sqrt{\left(\left(\frac{\Delta\left(\frac{(M_c C_c)}{M_w}\right)}{\left(\frac{M_c C_c}{M_w}\right)}\right)^2 + \left(\frac{\Delta\left(\frac{Ti_c - Te_c}{Ti_w - Te_w}\right)}{\left(\frac{Ti_c - Te_c}{Ti_w - Te_w}\right)}\right)^2\right)} \tag{18}$$

Where: $\Delta\left(\frac{M_c C_c}{M_w}\right)$ is the error in the $\left(\frac{M_c C_c}{M_w}\right)$ term of the specific heat capacity equation; $\Delta\left(\frac{Ti_c - Te_c}{Ti_w - Te_w}\right)$ is the error in the $\left(\frac{Ti_c - Te_c}{Ti_w - Te_w}\right)$ term of the specific heat capacity equation.

$$\Delta C_{w1} = C_{w1}\sqrt{\left(\frac{\Delta\left(\frac{(M_cC_c)}{M_w}\right)}{\left(\frac{M_cC_c}{M_w}\right)}\right)^2 + \left(\frac{\Delta\left(\frac{Ti_c - Te_c}{Ti_w - Te_w}\right)}{\left(\frac{Ti_c - Te_c}{Ti_w - Te_w}\right)}\right)^2} \tag{19}$$

Thus, from $C_w = C_{w1} \pm \Delta C_{w1}$,

$$C_w = C_{w1} + C_{w1}\sqrt{\left(\frac{\Delta\left(\frac{(M_cC_c)}{M_w}\right)}{\left(\frac{M_cC_c}{M_w}\right)}\right)^2 + \left(\frac{\Delta\left(\frac{Ti_c - Te_c}{Ti_w - Te_w}\right)}{\left(\frac{Ti_c - Te_c}{Ti_w - Te_w}\right)}\right)^2} \tag{20}$$

2.5 Data analysis

Data were statistically analyzed using Analysis of Variance (ANOVA) and Duncan's Multiple Range Test to compare the means (at 95% Confidence level).

3 RESULTS

3.1 Thermal conductivity and resistance

Mean thermal conductivities from different directions of *C. pentandra* samples, presented in Figure 8, show that treated stakes produced greater values for Maneb/Lambda [$(0.006 \pm 0.0006) \times 10^{-3}$ W/m.K] and *E. suaveolens* [$(0.005 \pm 0.001) \times 10^{-3}$ W/m.K] than the control/untreated, which had $(0.004 \pm 0.0008) \times 10^{-3}$ W/m.K. The differences were significant. Conductivity was greater for Maneb/Lambda-treated stakes than for those preserved with *E. suaveolens*. Conductivity was greater at the longitudinal directions for Maneb/Lambda and *E. suaveolens*-treated stakes [$(0.04 \pm 0.0002) \times 10^{-3}$ and $(0.039 \pm 0.0008) \times 10^{-3}$ W/m.K, respectively] than at the radial [$(0.038 \pm 0.004) \times 10^{-3}$ and $(0.037 \pm 0.0004) \times 10^{-3}$ W/m.K respectively] and tangential surfaces: $(0.037 \pm 0.0002) \times 10^{-3}$ and $(0.036 \pm 0.005) \times 10^{-3}$ W/m.K, respectively. The differences were significant ($p<0.05$).

Thermal resistance was greater for the control [$(0.12 \pm 0.0008) \times 10^2$ – $(1.02 \pm 0.02) \times 10^2$ m^{2}K/W] than the treated stakes [$(0.1 \pm 0.002) \times 10^2$ – $(0.76 \pm 0.02) \times 10^2$ and $(0.1 \pm 0.002) \times 10^2$ – $(0.73 \pm 0.02) \times 10^2$ m^{2}K/W for *E. suaveolens* and Maneb/Lambda respectively] (Figure 9). There were no

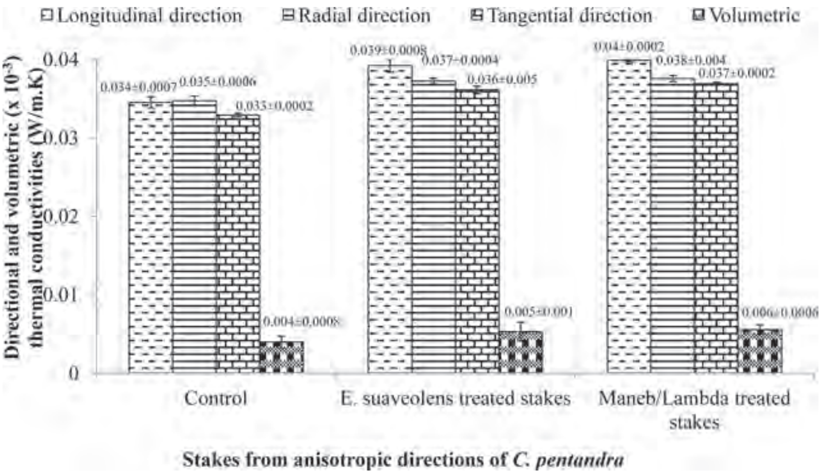

FIGURE 8
Thermal conductivity of treated and control stakes from anisotropic directions of *C. pentandra* (Bar = SE; n = 10).

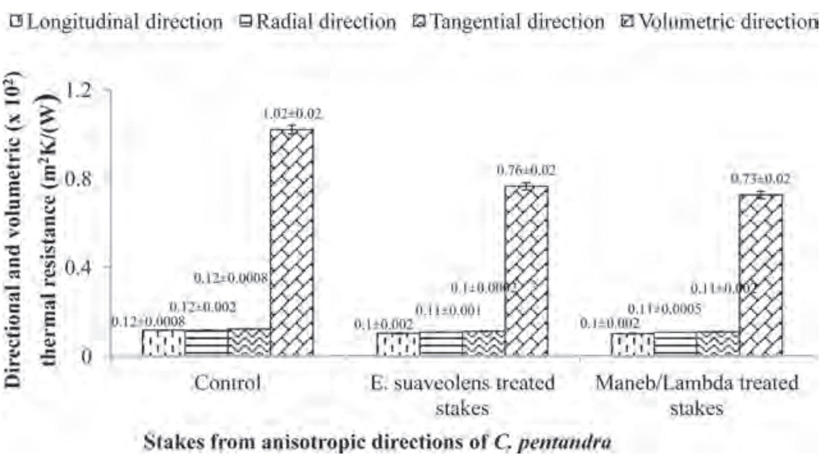

FIGURE 9
Thermal resistance of treated and control stakes from anisotropic directions of *C. pentandra* (Bar = SE; n = 10).

significant differences in thermal resistance along the anisotropic directions for the control, Maneb/Lambda- and *E. suaveolens*-treated stakes.

3.2 Specific heat capacity

Figure 10 shows that greater Specific Heat Capacities were recorded for *E. suaveolens* and Maneb-Lambda-treated stakes [$(5242.1 \pm 269.9) \times 10^6$ and $(6810.9 \pm 12) \times 10^6$ J. kg^{-1} k^{-1} respectively] than for the control

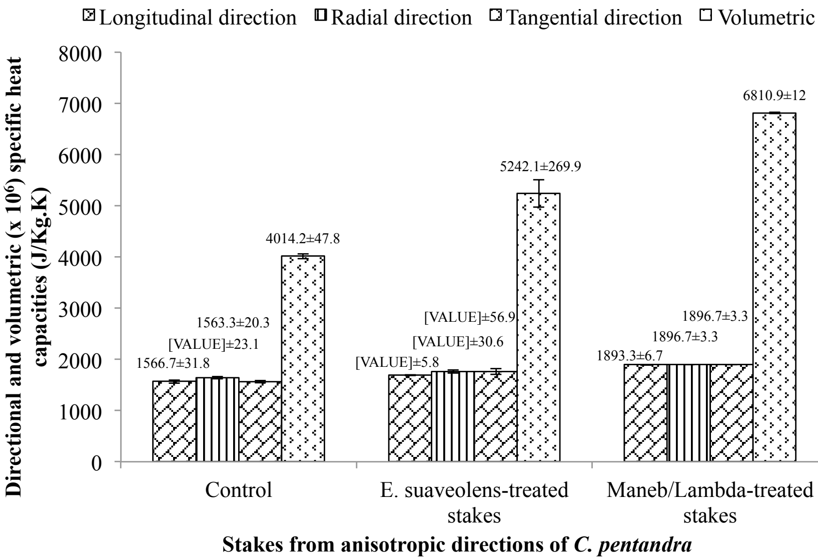

FIGURE 10
Specific Heat Capacity of treated and control stakes from different directions of *C. pentandra* (Bar = SE; n = 3).

[(4014.2 ± 47.8) × 10^6 J. kg^{-1} k^{-1}]. Heat Capacity along the stake directions/surfaces varied: those from Maneb/Lambda produced the greatest heat capacity in the tangential and radial directions [(1896.7 ± 3.3) × 10^6 J. kg^{-1} k^{-1}], followed by those of *E. suaveolens* [(1760 ± 30.6) × 10^6 and (1760 ± 56.9) × 10^6 J. kg^{-1} k^{-1} respectively] and the control [(1563.3 ± 20.3) × 10^6 and (1640 ± 23.1) × 10^6 J. kg^{-1} k^{-1} respectively]. Nonetheless, the differences were not significant ($p>0.05$). The Specific Heat Capacity in the longitudinal direction was as follows: (1893.3 ± 6.7) × 10^6, (1690 ± 5.8) × 10^6 and (1566.70 ± 31.8) × 10^6 J. kg^{-1} k^{-1} for Maneb/Lambda, *E. suaveolens* and the control, respectively.

4 DISCUSSION

4.1 Thermal conductivity and resistance

Materials with high conductivity and low thermal resistance such as steel and aluminium easily conduct heat into the interior space of buildings, which causes discomfort to the occupants. [50] mentioned that in many industrial applications, including construction of building envelopes, a material's thermal conductivity and resistance are important properties worth considering for its selection since they indicate its insulation capabilities. Since the main function of thermal insulation materials in buildings is to reduce the transmission of heat, the best wood materials, especially those for roofing design, should have the lowest thermal conductivity and high thermal resistance in order to reduce the total effect of heat transmission [13, 55–57]. Thermal conductivities for all the *C. pentandra* stakes (treated or control) remained lower than those for other building materials such as steel (45 *W/m. K*), aluminium (216 *W/m. K*) and concrete (0.9 *W/m. k*) [10, 13]. Their resistance to heat flow [$(0.73 \pm 0.02) \times 10^2 - (1.02 \pm 0.02) \times 10^2$ m^2K/W] was also greater than those of aluminium (0.61 m^2K/W), single pane glazing (0.91 m^2K/W) and asphalt shingles (0.94 m^2K/W). [5] noted that such low thermal conductivities and high thermal resistance for *C. pentandra* could be due to its porosity and paucity of free electrons in it, which are responsible for an easy transmission of energy. This would justify the use of treated and untreated wood in buildings where thermal comfort is highly desirable as compared to steel, concrete and several other building/construction materials [13, 57]. Treated stakes slightly produced greater conductivities and lower resistance than the untreated. This confirms the assertion by [7] that the thermal conductivity and resistance of wood is dependent on the conductivity and resistance values of its chemical substances such that the individual salts making up the organic and inorganic preservatives increased the overall conductivities of the treated wood while reducing their resistance. This might account for the greater conductivities for the *E. suaveolens*- and Maneb/Lambda-treated stakes than their untreated/control counterparts. [7] noted that the anisotropy of wood complicates the solution to heat and mass transfer problems, which require that analyses be based on fundamental material properties of the wood structure. [13] reported differences in conductivity among different directions of wood. [58] also observed greater conductivity in the tangential direction than the radial and longitudinal surfaces of Douglas fir; although no significant difference occurred between the tangential and radial conductivities. The present study shows significant differences ($p<0.05$) between the three directions of the control, as well as those treated with Maneb/Lambda and *E. suaveolens*, which is consistent with the works by [59] and [60]; their studies demonstrated significant differences between the thermal conductivities at the longitudinal, radial and tangential surfaces of their untreated wood. The present study also shows that the longitudinal direction had the greatest conductivity values for both treated and untreated stakes, which is in agreement with the work by [61]. [7] and [10] explained that the microfibrils in the S_2-layer of wood are nearly parallel to the longitudinal axis of the cell. This orientation facilitates heat transfer and is responsible for the large conductivity values obtained in longitudinal surfaces. Generally, this work has indicated that heat transfer rate in all the surfaces of *C. pentandra* stakes (untreated and treated) was significantly different ($p<0.05$), which implies that *E. suaveolens* extract and Maneb/Lambda greatly altered conductivity and resistance in the three directions. Thus, based on thermal conductivity and resistance, treated *C. pentandra* could be used in providing thermal insulation in much the same way as their untreated counterparts.

4.2 Specific heat capacity

The greater Specific Heat Capacities observed for the treated stakes than those of the untreated stakes could be attributed to the specific heat capacities of the various salts in the chemicals for the wood treatment [10]. [24] found that individual elements within an insulating material substantially influenced its average Specific Heat Capacity. In real world application, this would mean that treated wood would need a lot of thermal energy to be warmed and generate heat compared to their untreated counterparts. For the stakes treated, those impregnated with Maneb/Lambda mixture produced greater heat capacity than *E. suaveolens* extracts [15]. This implies that, in terms of insulation, Maneb/Lambda-treated wood would perform better, as it would require more thermal energy to heat it from its cold state than those with *E. suaveolens* or the untreated/control [10, 15]. [24], [9] and [10] found no influence of the orientation of wood cells (i.e., grain direction) on the specific heat capacity of timber. The present results confirm this assertion. Furthermore, unlike the case of thermal conductivity, the chemicals applied for the treatment of the stakes did not significantly affect their heat capacities at their various surfaces, as there was no steady trend for the variation in their energy values.

5 CONCLUSION

- Thermal conductivity was greater for chemically-treated stakes than the untreated/control; longitudinal surface than at the radial and tangential directions of the stakes.
- However, conductivity of the treated and untreated *C. pentandra* stakes was lower than those of other building materials (e.g. steel, aluminium and concrete). Similarly, thermal resistance was greater for both treated and untreated stakes than those of materials frequently used for the construction of building envelopes.
- For the treated stakes, those impregnated with Maneb/Lambda had greater heat capacity than those with *E. suaveolens* and then the control.
- Orientation of wood cells (i.e., grain direction) did not influence the Specific Heat Capacity of *C. pentandra*.
- In all, treated stakes have low thermal conductivity with high thermal resistance and Specific Heat Capacity, a desired property as an insulation material. Thus, non-durable woods could be chemically-treated against bio-deterioration, while maintaining their ability to provide thermal comfort in buildings.

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NOMENCLATURE

Symbol	Meaning	SI unit
k	Thermal conductivity	W/m.K
R	Thermal resistance	m^2K/W
c	Specific heat capacity	J. kg^{-1} k^{-1}
m	mass	kg
T	Temperature	°C
Q	Heat	J
A	Cross sectional area	m^2

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