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DETERMINATION OF HEAT TRANSFER PROPERTIES OF VARIOUS PVC AND NON-PVC CEILING MATERIALS AVAILABLE IN NIGERIAN MARKETS

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ABSTRACT

In this study, heat transfer properties of 10 polyvinyl chloride (PVC) ceiling composites and 4 other non-PVC ceiling materials, such as particle board, cardboard, plywood and asbestos were determined using an automated Lee's disc apparatus and XRY-1C bomb calorimeter. Results obtained indicated that asbestos were consistent in being inert to ignition in addition to having the lowest specific heat capacity (SHC). Polyvinyl chloride ceiling composites had advantageous thermal conductivities in comparison to the non-PVC ceiling materials. The SHCs and thermal characteristics of ceiling materials for building constructions and other applications should be appraised by manufacturers where combustion requirements are of utmost consideration.

Keywords: Thermal combustion; characteristics; heat of combustion; bomb calorimeter; heat transfer

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1. INTRODUCTION

The desire for an aesthetic environment and thermal comfort is an inherent trait of modern buildings [1, 2]. This is why the choice of a ceiling material is influenced by advancement in technology and societal influence. Plant-originated ceiling materials, such as thatches, plywood and cardboard ceiling are gradually giving way to synthetic and composite ceiling materials, such as asbestos, plaster of Parish (POP) and the more recently PVC [2]. The knowledge of thermal conductivity is very important with respect to the general suitability and transport phenomenon of materials used for ceiling purposes [3]. In the analysis of Polyetheretherketone (PEEK), the specific heat capacity and temperature decreased when the particle content was increased due to the differences in the composite composition [3]. It has been argued that there are factors, such as moisture content and temperature, responsible for the thermal conductivity of insulating materials even though constant values were used [4]. Insulating material is important in building enclosure to reduce energy consumption and space heating in buildings which will be dependent on their thermal properties. The insulation property of material, such as temperature, can be controlled so as to achieve desired condition [5]. Varying the thermal conductivity of some materials could be desirable based on the type of application they are meant for [6]. The thermal conductivities of some materials which were endorsed as building materials have been investigated by various authors [7-11,13-15] their results showed that the discrete properties of the materials will fail when continuously exposed to extreme fire scenario due to the thickness variation and elemental characteristics of the materials. The elemental makeup of a material can be used to envisage the degree of combustibility of the material [12]. The mass residue of combustion is a reflection of either the ceiling sample undergoes a complete or an incomplete combustion as shown in figure 1 below.

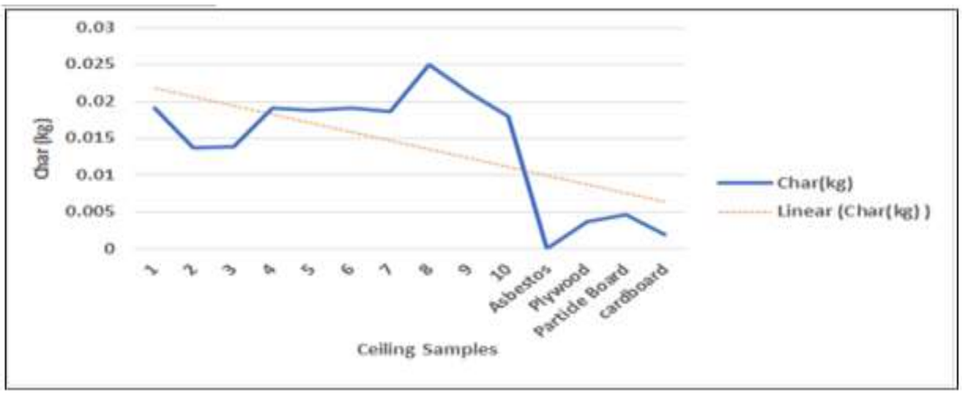


Figure 1 Experimental analysis of the char (kg) vs. burn-out time(s). Source: Dirisu *et al* (in press)

These thermal conductivities will help to ignite the industrial revolution and also increase the productions output of the PVC materials in the manufacturing company [25-33].

However, the aim of this study was to establish the extent of suitability of PVC materials and other ceiling materials available in Nigerian markets for ceiling purposes by comparing the specific heat capacities and heat transfer characteristics of the various materials.

2. MATERIALS

Fourteen (14) commonly used samples of ceiling materials comprising 10 PVC and 4 other non-PVC ceiling materials, such as particle board, cardboard, plywood and asbestos were obtained from various retailers and wholesalers in Nigeria. Three of the 10 PVC were made in Nigeria, while the remaining were composite PVCs imported to Nigeria and were common in most of the PVC ceiling materials outlets visited; this informed the careful selection of the seven non-Nigerian products. The instrument used included electronic beam balance, jigsaw, Vernier caliper, beaker, water, copper calorimeter and stirrer, automated Lee's disc apparatus and XRY Bomb Calorimeter system. The XRY-1C bomb calorimeter is shown in figure 2. The samples collected are presented in Figure 3.

Figure 2 XRY-1C Oxygen Bomb Calorimeter and Oxygen Cylinder

3. METHOD

The sample was weighed on an electronic beam balance and its mass recorded as $M_{Ceiling}$. A beaker was filled with water; the suspended sample was placed inside it at boiling point of 100^oC and left to be heated for about five minutes. Also, a copper calorimeter was weighed together with the stirrer and the mass was recorded as M_{cal}. It was later half-filled with water and reweighed to obtain a new mass M_{mix}. Thermometer was inserted in it and the initial temperature $\theta_1$of the water was recorded. The calorimeter water was brought to boiling and the temperature of the boiling water was measured and recorded as θ_2. The ceiling material was quickly transferred to the water in the calorimeter. The water was stirred continuously but gently and the highest temperature was read as θ_3 [18].

Mass of ceiling, $M_{Ceiling}$=………………g

Mass of calorimeter & stirrer, M_{cal}=……………………g

Mass of calorimeter + water, M_{mix} =……………………...g

Initial temperature of water (i. e. temp. of solid) is θ_2, =……… ^oC

Final temperature of mixture θ_3=……………………………… ^oC

Specific heat capacity (S.H.C.) of solid $C_{ceiling}$=…………………………..$Jkg^{-1}K^{-1}$

S.H.C. of copper calorimeter C_{cal} = 385 $Jkg^{-1}K^{-1}$

S.H.C. of water C_{water} = 4200 $Jkg^{-1}K^{-1}$

Ignoring any heat losses to the environment,

Heat lost by Ceiling Sample = Heat gained by water + Heat gained by copper calorimeter and stirrer.

$$M_{ceiling}\, Cc_{eiling}\,(\theta_2 - \theta_3) = (M_{mix} - M_{cal})\, C_{water}\,(\theta_3 - \theta_1) + M_{cal}\, C_{cal}\,(\theta_3 - \theta_1) \; [4]$$

From the above formula, the specific heat capacity of the samples will be calculated as stated below[18]:

$$C_{ceiling} = \frac{(Mmix - Mcal)\ Cwater\ (\theta3 - \theta1) + Mcal\ Ccal\ (\theta3 - \theta1)}{Mceiling(\theta2 - \theta3)}\ Jkg^{-1}K^{-1}$$

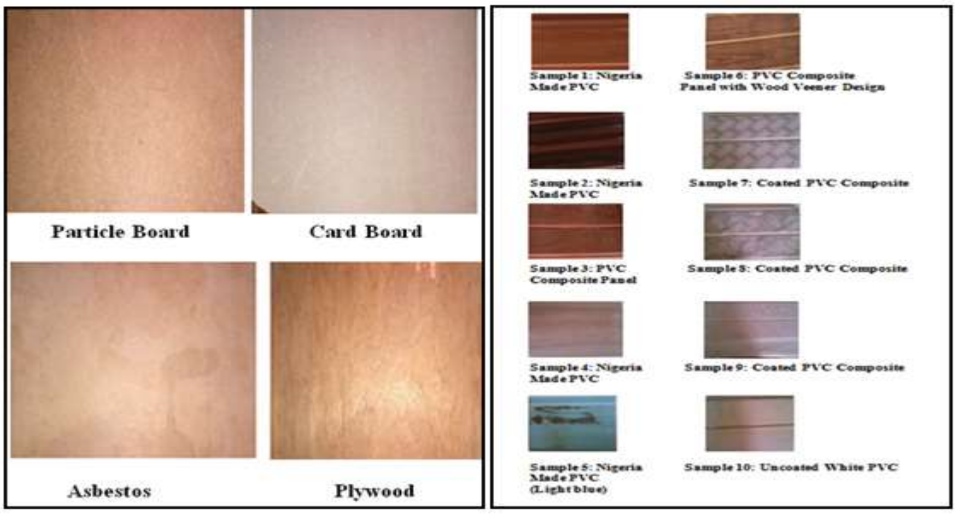


Figure 3 Collections of PVC and non-PVC Samples

3.1. Thermal conductivity determination

The thermal conductivities of the 14 samples were determined using automated Lee’s Disc apparatus (Figure 5), having upper and lower disc both of 50 mm diameter. The sample cut into 50 mm diameter with a jigsaw was placed in-between the upper and lower disc so that heat was supplied at a steady state from the source to the sample and to the sink at a temperature-controlled environment. The cut circular profile is shown in figure 4.

The automated Lee’s Disc apparatus contained a heating element coupled with a thermocouple attached to the heat source and sink and preset to an initial temperature of 50^{o}C. The temperature supplied to the base plate was taken at every 5 minutes for sixty minutes after which the sample is removed then the metal disc is heated to 10^{o}C above the heating temperature. The plate was then allowed to cool off steadily for 5 minutes below the final heating temperature to determine the rate of heat loss from the base plate. The experiment was repeated thrice for each of the 14 samples in a controlled environment. The thickness, dx, of the samples were determined using a Vernier caliper and cross-sectional area, A, determined by calculation from fixed 50 mm diameter marked out with a pair of compass and cut to size with a jig saw.

Circular profile of PVC and non-PVC ceiling   Jig saw cutting PVC panel to circular profile

Figure 4 Circular Profile of the Ceiling Materials

Figure 5 Automated Lee's Disc Apparatus Views Sources: Paul and Fagbenle, 2014

3.2. Other thermal parameters

The measurement of the thermal conductivity (k), true density (ρ), and specific heat capacity (C), of the samples enabled the determination of the value of thermal diffusivity of the material to be made. The thermal diffusivity is given as:

$$\alpha = k/\rho C_p \qquad [1]$$

where *k*, ρ and C_p *represent* the thermal conductivity, the mass density, and the specific heat at constant pressure, respectively.

The thermal diffusivity α is then used to calculate the thermal inertia [19, 20],

$$I = [k\rho c]^{1/2} \quad J\, m^{-2}k^{-1}s^{-1/2} \qquad [2]$$

The reciprocal of thermal conductivity gives the thermal resistivity, usually measured in Kelvin-meters per Watt (KmW^{-1}),

$$R = 1/k \qquad [3]$$

where R is the thermal resistivity, and k is thermal conductivity.

When dealing with a known amount of material, its thermal conductance and the reciprocal property, thermal resistance, can be described.

4. RESULTS AND DISCUSSION

Table 1 shows the elements present in selected ceiling materials which gives a fore view of the behaviour of the ceiling materials during combustion. The automated Lee's Disc thermal conductivity apparatus for solid materials was designed by Philip and Fagbenle [16]. The variation in the relationship between temperature and specific heat capacity of two materials such as composite shape-stabilized phase change material and asphalt mixtures was established [17].

The mean specific heat capacities of various ceiling samples (Table 2) indicated that asbestos had the overall lowest SHC value of 848.311 J/kg K while cardboard had the highest

SHC value 9423.972 J/kg K. The analysis also showed that the SHC values of the PVC materials was greatest in sample 2 (Nigerian made PVC), and lowest with sample 10 (uncoated white PVC). This established that cardboard would generate highest thermal energy, while asbestos would give the least thermal energy.

Table 1 Elemental make-up of Selected Ceiling materials

	Elemental Composition (%)													
Samples	O	C	N	Si	Cl	Na	Ca	K	Al	Ti	Pb	Fe	S	Mg
PVC 3	63.6	15.9	10.6	3.5	2.2	2.0	1.0	0.5	0.5	0.1	0.01	-	-	-
PVC 7	18.0	77.9	3.0	0.2	0.23	0.2	0.2	0.1	0.05	0.1	-	-	-	-
PVC 10	18.0	77.9	3.0	0.2	0.23	0.2	0.1	0.1	0.05	-	0.02	0.1	-	-
Particle Board	39.0	56.7	-	0.2		0.2	1.7	-	0.05	0.1	-	-	2.1	-
Plywood	62.0	30.4	-	0.2	2.1	0.2	1.4	-	0.05	0.1	-	-	2.0	1.5
Cardboard	76.0	10.0	-	0.2	0.6	0.2	5.1	-	0.05	0.1	-	-	0.8	1.5

Source: Dirisu *et al.*[12]

Table 2 Specific Heat Capacity of PVC and non-PVC samples

SAMPLE	**MASS (kg)**	**Mean± s.d.(J/kgK)**
Sample 1	0.0016	2224.397±22.73191
Sample 2	0.0006	4016.404±480.2877
Sample 3	0.0012	1804.665±227.4756
Sample 4	0.0015	2353.661±176.7182
Sample 5	0.0016	2008.227±172.3808
Sample 6	0.0022	1615.764±151.4116
Sample 7	0.0017	1472.249±160.901
Sample 8	0.0014	2796.892±629.0124
Sample 9	0.0020	2250.780±382.7896
Sample 10	0.0026	1255.880±115.4676
Asbestos	0.0069	848.3107±32.71721
Cardboard	0.0028	9423.972±163.9509
Particle board	0.0082	5458.435±971.9666
Plywood	0.0026	5041.797±423.5527

4.1. Thermal properties of samples

All samples showed low thermal conductivity as seen in Table 3. This might be because they are all insulators. Seven of 10 PVCs recorded low thermal conductivity values with sample 5 showing the least (0.0240 W/mK). Particleboard had the overall highest thermal conductivity with the value 0.4730 W/mK which implies that it will conduct heat the most compared to other samples and will become unsafe in the course of fire outbreak. Particleboard showed the lowest thermal resistivity value of 2.1 kmW^{-1}; hence heat can percolate within and along the grains of this sample more than the PVCs with higher values. This means that it can spread fire faster. The thermal diffusivity of all the samples was generally low falling in the range of 0.0021 – 1.3419 ($\times 10^{-6}$ m^2/s). This is a function of their low thermal conductivity and high specific heat capacity.

The results further showed that the thermal inertia (110.860 $\text{J/m}^2\text{ks}^{1/2}$) was lowest for sample 5 implying that it will cool fastest with time, while the thermal inertial was highest for particle boards with values of 110.86 and 4037.11 J/ ($\text{m}^2\text{ks}^{1/2}$). Hence, these will store heat and will not release it readily to the environment. Thermal values are shown in Table 3.

Table 3 Thermal properties of samples

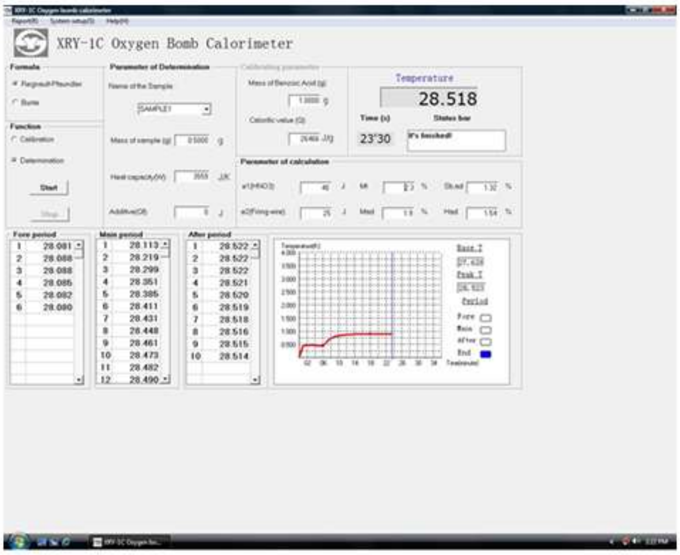
	Density	Specific Heat Capacity	Thermal Conductivity	Thermal Resistivity	Thermal Diffusivity	Thermal Inertia
	ρ (Kg/m^3)	c (J/KgK)	k (W/mK)	R (km/W)	α (m^2/s) x 10^{-6}	I (J/m^{2}ks$^{1/2}$)
Sample 1	407.000	2224.400	0.0410	24.450	0.050	192.440
Sample 2	237.000	4016.400	0.1610	6.230	0.170	390.900
Sample 3	265.000	1804.670	0.0550	18.140	0.115	162.400
Sample 4	305.000	2353.660	0.0520	19.240	0.072	193.160
Sample 5	254.000	2008.230	0.0240	41.500	0.050	110.860
Sample 6	143.000	1615.760	0.0920	10.820	0.400	146.130
Sample 7	125.000	1472.250	0.2500	4.050	1.342	213.180
Sample 8	611.000	2796.900	0.0800	12.570	0.047	368.720
Sample 9	356.000	2250.780	0.0600	16.570	0.075	219.940
Sample 10	2540.000	1255.880	0.0660	15.150	0.208	1446.540
Asbestos	18100.000	848.310	0.3700	2.700	0.024	2383.140
Cardboard	7150.000	5458.440	0.0810	12.400	0.002	1774.400
Particleboard	6840.000	5041.800	0.4730	2.120	0.014	4037.110
plywood	5970.000	9423.970	0.2170	4.600	0.004	3496.100

The result shows that heat flux for non-PVCs are significantly high when compared to PVC samples with plywood having the highest value of 23.86W/m^2 as shown in table 4.

Table 4 Heat Flux (q$''$) of Ceiling Samples

Sample	x (m) X10^4	A (m$_4$) x 10	K (Wm^{-1}K^{-1})	t$_1$ (°C)	t$_2$ (°C)	dT(°C)	Q=(kA).(dT/x)	q"=Q/A HeatFlux
1	2.000	19.640	0.041	47.700	50.000	2.300	0.00018	0.940
2	3.000	19.640	0.161	49.000	50.000	1.000	0.00021	1.050
3	2.500	19.640	0.055	48.000	50.000	2.000	0.00017	0.870
4	2.000	19.640	0.052	48.300	50.000	1.700	0.00017	0.850
5	3.000	19.640	0.024	44.000	50.000	6.000	0.00019	0.950
6	5.000	19.640	0.092	47.300	50.000	2.700	0.00019	0.970
7	6.500	19.640	0.250	48.700	50.000	1.300	0.00020	0.990
8	1.000	19.640	0.080	49.300	50.000	0.700	0.00021	1.040
9	2.000	19.640	0.060	48.300	50.000	1.700	0.00019	0.980
10	4.000	19.640	0.656	50.300	50.000	0.300	0.00021	1.070
Asbestos	2.900	19.640	0.370	46.300	50.000	3.700	0.00180	9.180
particle B	9.900	19.640	0.081	35.700	50.000	14.300	0.00045	2.290
Plywood	3.500	19.640	0.473	41.000	50.000	9.000	0.00469	23.860
Card board	3.500	19.640	0.217	42.700	50.000	7.300	0.00176	8.94

The calorific values of each sample are shown in Figures 6 and Tables 5 above. The results show that heat flux for non-PVCs were significantly high when compared to PVC samples with plywood having the highest value of 23.86 W/m^2. Particleboard had the highest heat of combustion of 45.666 J/kg while asbestos failed to ignite; as it only became brittle over time; hence no calorific value. By implication, asbestos could be regarded as the safest ceiling material in terms of resistance to combustion in the cause of fire outbreak. This was due to the flame retardant and elemental properties inherent the asbestos [21]. The shortfall of this material is that it causes cancer of the lung after much inhalation and exposure [22]. The Nigerian Building Code and related articles had placed a warning on the usage of asbestos ceiling [21 – 23]. Non-PVC samples, except asbestos, ignited without having a trace of char in the crucible of the oxygen bomb calorimeter. This further established that asbestos was safe as it would not support fire outbreak. The time, x, of combustion of all samples in the bomb calorimeter was within the range $23.5 \leq x \leq 33.0$ minutes.



Name of the Sample: SAMPLE1

Mass of sample (g): 0.5000 g

Temperature: 28.518

Time (s): 23'30

States bar: It's finished!

	Fore period	Main period	After period
1	28.081	28.113	28.522
2	28.088	28.219	28.522
3	28.088	28.299	28.522
4	28.085	28.351	28.521
5	28.082	28.385	28.520
6	28.080	28.411	28.519
7		28.431	28.518
8		28.448	28.516
9		28.461	28.515
10		28.473	28.514
11		28.482	
12		28.490	

Figure 6 Bomb Calorimeter showing the calorific value of PVC sample 1

Table 5 Calorific values of PVCs and non-PVCs

Sample Name	Mass of Sample(g)	Heat Capacity(J/K)	Calorific Value(J/g)
Sample2	0.5000	2410	26466
Asbestos	0.5000	5853	26466
Sample 3	0.5000	2166	1790
Sample 4	0.5000	3531	1618
Sample 5	0.5000	3213	1191
Sample 6	0.5000	3531	3223
Sample 7	0.5000	2503	629
Sample 8	0.5000	2503	1541
Sample 9	0.5000	4502	1744
Sample 10	0.5000	3265	1538
Cardboard	0.5000	26387	36672
Plywood	0.5000	13109	14968
Particleboard	0.5000	44759	45666

The mass loss is a further verification of the level of combustion of each sample as revealed in figure 7. Asbestos remained inert and did not combust in the bomb calorimeter. Non-PVC samples had higher level of mass lost compared to PVC sample; thus they combusted more than the latter

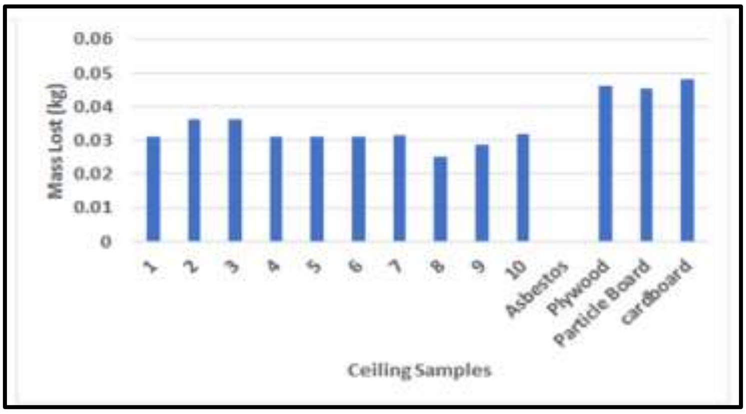


Figure 7 The graph of the mass lost (kg) vs. Samples of the PVC and other material

5. CONCLUSION

This study has established that asbestos would generate least thermal energy as a result of its low specific heat capacity while cardboard would conduct the most thermal energy. All the samples were low in their thermal insulation properties while sample 5, Nigerian made PVC light blue, was the most desirable as it had the lowest value. Particleboard as an insulator would conduct heat due to its low thermal resistivity. Due to higher heat flux, plant-based ceiling tiles such as plywood appeared to have higher heat-generating capacity in circumstances of fire outbreak than PVC composite types. The combustion behavior of plant-based ceiling types was further endorsed by their complete combustion in the bomb calorimeter. The fire retarding potential of asbestos as demonstrated in this study made it the safest among the ceiling materials studied. The time of combustion process of these materials did not exceed 33 minutes for both complete and incomplete combustion activities. On aesthetic premise, PVC ceiling materials are currently gaining wider acceptance over non-PVC materials without considering various implications in the event of a fire outbreak which needs to be a cogent reason for the choices of ceiling materials made by end users.

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