IGNITION TIME OF SELECTED CEILING MATERIALS AND ESCAPE TEMPERATURE TIME PREDICTION OF FIRE FIGHTER RESCUE MISSION

Dirisu Joseph Osekhoghene[1], Oyedepo Sunday Olayinka[1],
Fayomi Ojo Sunday Isaac[1,2], Okokpujie Imhade Princess[1]

[1] *Department of Mechanical Engineering, Covenant University P.M.B. 1023, Ota, Nigeria*
[2] *Department of Chemical, Metallurgical and Materials Engineering Tshwane University of Technology, P.M.B. X680, Pretoria, South Africa*
E-mail: imhade.okokpujie@covenantuniversity.edu.ng

Received 12 March 2018
Accepted 19 October 2018

ABSTRACT

This study investigated the ignition time of selected ceiling materials with the view to know the responses of the materials to flame if it is spontaneous or not and to report their suitability for use. In this study sample of polyvinylchloride (PVC) and plant originated ceiling materials from western and northern parts of Nigeria were used. PVC samples experienced spontaneous ignition due to their coating. 50 g of each sample was combusted in a purged local combustion stove. Thermocouple was used in measuring their temperatures at equal intervals. The residual sample mass was weighed with an electronic balance. The result showed that the ignitions of plant originated ceiling were spontaneous producing less mass loss and char when compared to those observed in case of PVC. The latter ignition time was attributed to its coating that ignited. Asbestos was unresponsive to the combustion process but it became brittle. It would have been an excellent fire-retardant ceiling material if not for the resultant health hazard called asbestosis. The minimum grand time for rescue operation while entering and leaving a fire compartment was 85 s.

Keywords: ignition time, fire retardant, rescue operation, grand time, fire compartment

INTRODUCTION

Fire is an exothermic reaction that releases heat energy in form of light and heat [1]. It is a manmade disaster [2] which is preventable. Factors that contribute to its spread are combustible materials [3], poor electrical wiring [4], failure to adhere to building codes [5]. A fire undergoes an *incipient*, a *growing,* a *fully developed*, and a *decay* stages [6], [24 - 26]. Materials propagating a fire refer to wall papers, foams, ceiling materials [7]. Fire is said to be a good servant and a bad master as well [8]. A material is categorized as flammable if it burns continuously after the energy source is eliminated [9]. Quantifiable numbers of organic materials are flammable and combustible. They are a good source of a fuel [10]. Ignition time is the time a flammable sample undergoes decomposition through high temperatures [11]. Materials that undergo combustion provide different emissions [12] determined by their composition, the degree of exposure to the fire and the analytical methods employed in the study. The thermal conductivity, the thermal absorptivity, the thermal resistivity and the specific heat capacity of PVC and asbestos are studied [13 - 17]. It is found that they are good insulating materials for ceiling purposes. The specification of ASTM D4477-16 [18] lists the physical requirements and the test methods for extruded single-wall soffits manufactured from rigid (unplasticized) PVC compounds. The latter when extruded into soffit always maintain a uniform colour. Besides, they are free of any visual surface or structural changes such as peeling, chipping, cracking, flaking, or pitting.

The release rate of PVC vapour is expressed as

$$\dot{m}'' = \dot{q}_n''/\Delta H_g \tag{1}$$

where $\dot{m}''$ is the release rate of PVC vapour per unit surface area of the material (g/m^{2}s), while $\dot{q}_n''$ is the net heat flux to the surface (kW/m^2) defined as:

$$\dot{q}_n'' = \dot{q}_e'' + \dot{q}_f'' - \dot{q}_{rr}'' \tag{2}$$

It is defined as the external heat flux per surface area of the polymer (kW/m²). $\dot{q}_f''$in Eq. (2) is the flame heat flux per unit surface area of the polymer (kW/m²), while ΔH_g is the heat of gasification (kJ/g), expressed as

$$\Delta H_g = \int_{T_a}^{T_m} c_s \, dT + \Delta H_m + \int_{T_m}^{T_v} c_1 \, dT + \Delta H_v \quad (3)$$

Eq. (3) includes ΔH_m which stands for the heat of melting of the polymer (KJ/g), ΔH_v which is the heat of vaporization of the polymer (kJ/g). T_a, T_m, and T_v and are the initial, the melting, the vaporization and the decomposition temperature values (°C) of PVC, respectively; c_s and c_1 are the heat capacities of the original solid and the molten polymer (kJ/gk), correspondingly. Eqs. (1) and (2) show that the release rate of PVC vapour, which is very critical in governing the fire hazard, depends on the heat flux from the external heat source $\dot{q}_e''$ and from its own flame, $\dot{q}_f''$, the heat losses from the surface, $\dot{q}_{rr}''$, and the heat of gasification, ΔH_g. All four parameters depend on the generic nature and thermo physical properties of PVC and the environmental conditions [19].

Combustible polymers and all types of matter are potential fire associates [20]. The heat release rate for the combustion of solid polymer is expressed as

$$y_j/\Delta H_g)(\dot{q}_e + \dot{q}_f - \dot{q}_{rr}'') = f_j(\varphi_j/\Delta H_g)(\dot{q}_e'' + \dot{q}_f'' \quad (4)$$

$$\dot{Q}_{ch}'' = \left(\frac{\Delta H_{ch}}{\Delta H_g}\right)\left(\dot{q}_e + \dot{q}_f - \dot{q}_{rr}''\right) \quad (5)$$

$$= \gamma(\Delta H_T/\Delta H_g)(\dot{q}_e'' + \dot{q}_f'' - \dot{q}_{rr}'')$$

where…. is the mass generation rate of product *j* per unit surface area of the polymer (g/m²), y_j is the yield of product *j* (g/g), f_j is the generation efficiency of product *j* , φ_j is the maximum possible mass stoichiometric yield of the product, *j* (g/g), is the chemical heat release rate per unit surface area of the polymer (kW/m²), ΔH_{ch} is the chemical heat of combustion (kJ/g), ΔH_T is the net heat of complete combustion of the polymer (kJ/g), γ is the combustion efficiency determined by the ratio of ΔH_{ch} to ΔH_T. The term $y_j/\Delta H_g$ is defined as the product generation parameter PGP (g/kJ), while the term $\Delta H_{ch}/\Delta H_g$ is defined as the heat release parameter (HRP, kJ/kJ) [19]. *fj* is the fuel carbon atom conversion efficiency. It is defined as the ratio of the experimental yield of a product *j* to the maximum possible stoichiometric yield of the product. The chemical heat release rate is the actual heat that is released in the combustion of a polymer [19]. It has a convective and a radiative component. It is always less than the heat release rate referring to the complete combustion as the polymers do not burn completely. The chemical heat release rate is determined by the mass generation rate of CO_2 corrected for the mass generation rate of CO (determined by carbon dioxide generation calorimetry) and by the mass depletion rate of O_2 (determined by oxygen consumption calorimetry). A thermocouple is a useful instrument to sense, measure, control and convert temperature change into electricity. It responds quickly to the temperature change and can operate at high temperatures [21 - 23].

Different modes of heat transfer interactions are observed in a burning ceiling. When the latter is considered as a slab, conduction and convection are worth mentioning.

Conduction is the mode of transfer due to the temperature difference in a constant channel. The energy transfer is directed by the high temperature heat source in the fire to the homogeneous sample ceiling material. Part of the energy is absorbed by the latter. This contributes to the temperature decrease in the fluid flow [22].

$$\dot{C}_X = -\dot{J}\frac{\partial P}{\partial x} \quad (6)$$

where j is the constant of proportionality ($\frac{W}{(m^o C)}$),

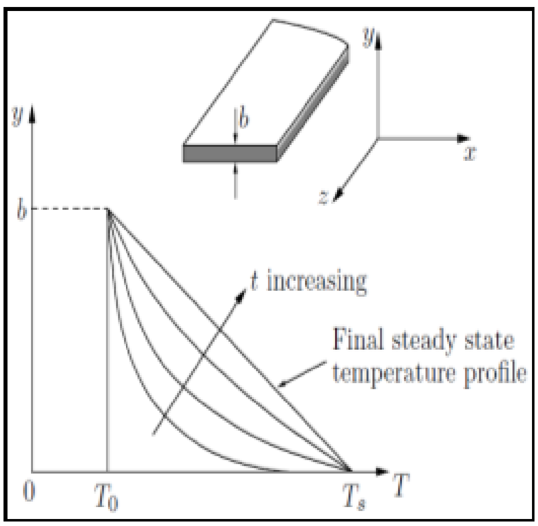

Fig. 1. Heat conduction through a slab presenting a ceiling sample [22].

called thermal conductivity,
$\dot{C}_X$ is the heat flux in W/m^2, while $\frac{\partial P}{\partial x}$ is the temperature gradient along the direction of flow in $^oC/m$.

The energy transferred to the room space by convection is defined as [23]

$$\ddot{C}=h(T_s-T_\infty) \quad (7)$$

where $\ddot{C}$ is the heat flux (W/M^2), h is the heat transfer coefficient (W/m2 K), T_s is the temperature of the surface (K or ^OC), while T_∞ is the free stream temperature (K or ^oC) [21].

The purpose of this work is to predict the maximum time of rescue and that of escape of fire fighters and victims interacting involuntarily with the flames. This requires the identification of the stages of combustion involved in various ceiling materials. Those which withstand combustion will be recommended for further improvement.

EXPERIMENTAL

Various brand of PVC material and plant originated ceiling samples were obtained from dealers and construction sites in Osun and Lagos State in Nigeria. They were representative of what could be found in other states. The experimental procedure used was as follows: 14 ceiling samples (10 were PVC, while the rest referred to the plant materials chosen) of 50 g were prepared using a weighing balance. The combustion apparatus was set up at an area clear from any buildings so that the fire could be controlled. Charcoal was fed into it and fuel was injected. Red hot coal purged of ashes was obtained. Wire mesh was introduced to accommodate each sample. Open combustion type was employed representing open channels like windows and doors. The temperature of the coal and each sample was obtained when a thermocouple probe was fed into the burning sample. The temperature variation with time was followed. Stop watch was used to take readings of the sample at intervals of 10 s up till the point the fire was finally extinguished. The procedure was repeated to minimize the error.

Terms employed in this experiment:

Ignition time, $t_{ignition}$ (the time of spontaneous or non-spontaneous ignition);

Burn out time, $t_{burn\text{-}out}$ (the time of material burning after fuel initiation; it depends on the type of the material employed, its thickness, the rate of reaction and the percolation of heat through the interstices of the material structure);

Spontaneous ignition (it refers to the self-sustained burning of the material after the application of fuel);

Char (the residue of the material after complete or incomplete combustion). It was evaluated on the ground of:

$$C = M_O - M_L \quad (8)$$

where C was the char obtained after discontinued combustion (kg), M_O was the original mass of the sample prior combustion, while M_L was the mass loss in the course of combustion.

Grand mean temperature (the mean temperature obtained on the ground of the experiments carried out). The formula used was:

$$T_{grand\ mean}=\frac{\sum T}{N} \quad (9)$$

where ∑T was the sum of the temperature values read (^oC), while N was number of r experiments carried out.

Grand time (calculated on the ground of the sum of the time intervals determined in the course of all experiments carried out). The formula below was used:

$$t_{grand\ mean} = \frac{\sum t}{n} \quad (10)$$

RESULTS AND DISCUSSION

Figs. 2 and 3 show the stages of combustion of the ceiling materials studied.

Samples 1 - 10 in Table 1 refer to PVC of no spontaneous ignition as combustion is not supported. Their smooth surfaces prevent the heat transport into the material microstructure. The rate of heat transportation through the interstices is further slowed down due to the reluctance of the element to support combustion. The ignition time experienced by these PVC is determined by the coating on the surface. The heat from the external source supports the decomposition of the samples. It results in emission of noxious gasses which have hazardous effects on the fire outbreak victim. Trusses made of a metal help preventing the fire spread unlike non-PVC

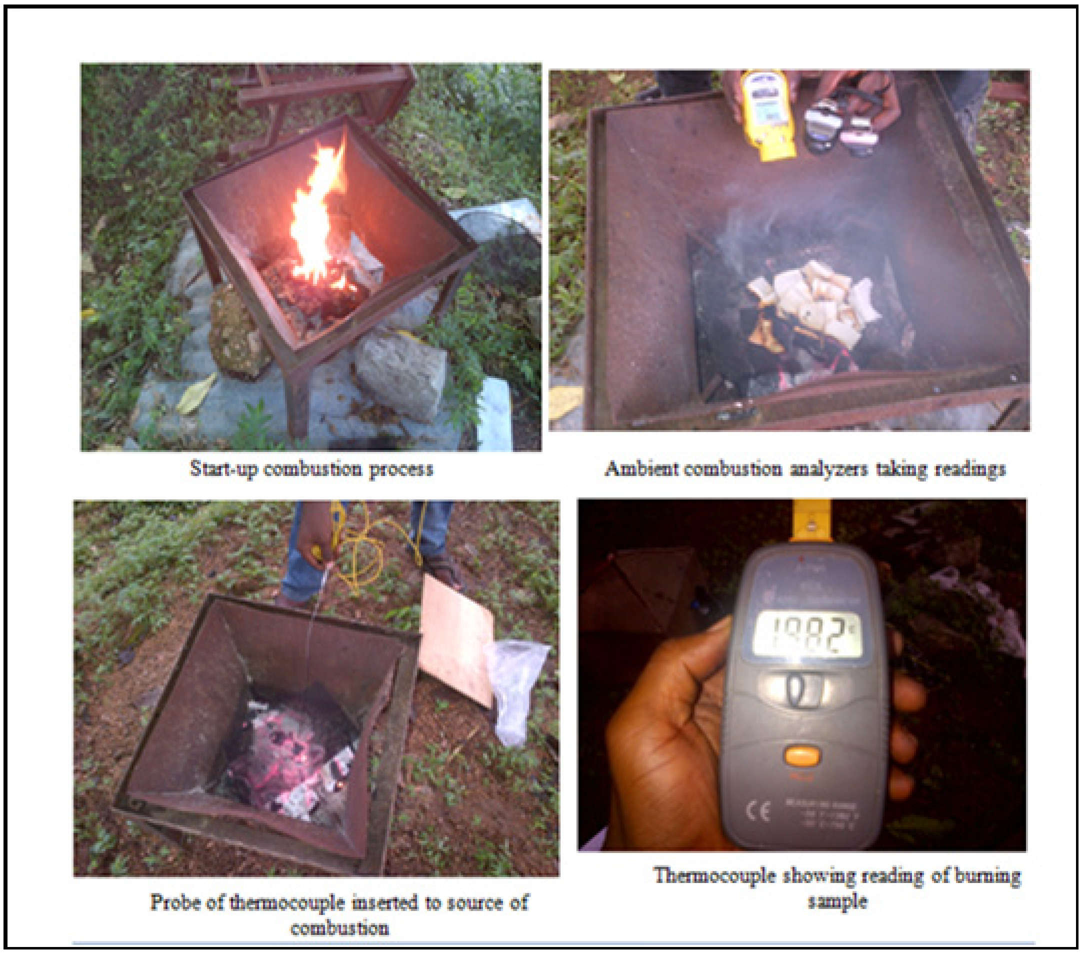

Fig. 2. The stages of the ceiling material combustion.

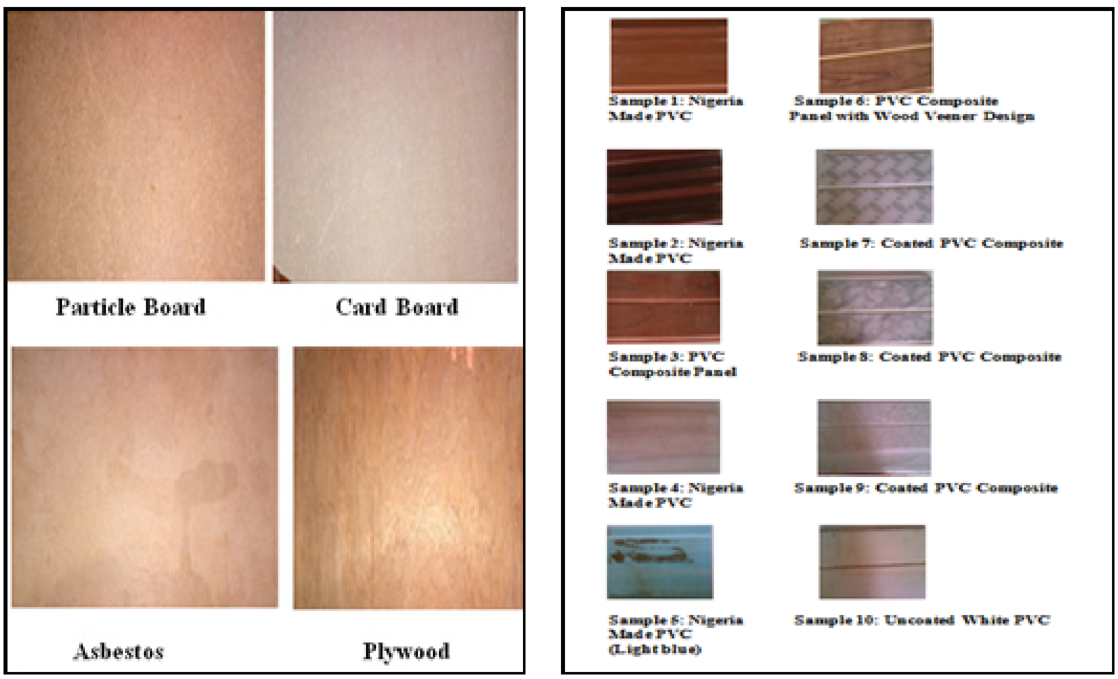

Fig. 3. Ceiling samples.

Table 1. Experimental combustion data.

Sample	Burn-out time (s)	Ignition time (s)	Spontaneous ignition Y=yes, N=no	Ignition temperature (°C)	Char(kg)	Mass lost(kg)
1	180.0000	10.0000	N	1861.0000	0.0191	0.0309
2	420.0000	13.0000	N	1620.0000	0.0137	0.0363
3	600.0000	-	N	-	0.0139	0.0361
4	180.0000	120.0000	N	1291.0000	0.0191	0.0309
5	180.0000	-	N	-	0.0189	0.0311
6	240.0000	60.0000	N	1438.0000	0.0191	0.0309
7	420.0000	5.0000	N	1512.0000	0.0187	0.0313
8	360.0000	120.0000	N	1540.0000	0.025	0.0250
9	720.0000	15.0000	N	1912.0000	0.0212	0.0288
10	180.0000	3.0000	N	1681.0000	0.0180	0.0320
Asbestos	NI	NI	N	NI	NI	NI
Plywood	300.0000	120.0000	Y	1853.0000	0.0037	0.0463
Particle Board	300.0000	7.0000	Y	1311.0000	0.0046	0.0454
Cardboard	180.0000	30.0000	Y	1131.0000	0.00199	0.0480

where NI simply means No Ignition

samples. The latter are spreading the fire irrespectively of the nature of the external trusses used to support the ceiling. Plywood, particleboard and cardboard show no trace of their structure due to the complete combustion as revealed by their masses of residues (char) (0.00370 kg, 0.00460 kg and 0.00199 kg, respectively). Hence these samples will encourage fire spread and can raze building with wooden trusses. As shown in Table 2, the highest and the lowest grand temperature time refer to 85 s and 70 s, correspondingly. Firemen should as a matter of urgency carry the rescue mission within these time limits. All samples temperature is beyond the flashover one which amounts to 600°C and pose a high risk to a victim trapped in a fire scenario.

The flame spread and the heat release ratings are factors employed to evaluate the degree of materials combustibility. The heat release rating implies the rate at which oxygen is consumed during combustion [27]. The maximum net peak heat release rate for a deck board is rated for 269 kW/m^2. Cone calorimeter equipments provide the determination of heat transfer parameters. The test criteria for non-combustible materials refer to:

- weight loss less or equal to 50%;
- no flame within 30 s;
- a material temperature not higher than 30°C above that measured in the test apparatus [27]. Materials that are ignition resistant survive 30 min of flame due to fire retardants impregnated in them. A horizontal flame spread tunnel is usually provided.

A fire resistant material on the other hand reveals a capability of fire hampering. Thus, there is enough time for the people to exit a burning building before it collapses. The performance of a single material does not depict the overall performance of the building as it is composed of a number of them. A non-combustible material will not burn does not release flammable vapour and does not ignite. It corresponds to the standard test carried out in a vertical tube furnace at 750°C [28]. Finishing materials for ceiling construction can be made of any material, except plastics, they can be included in homogenous or composite constructions, but subjected to control [30 - 31].

Table 2. Sample temperature –time data.

Time (s)	MEAN TEMPERATURE(℃)										
	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6	Sample 7	Sample 8	Sample 9	Sample 10	Asbestos
10	1065.5	1183.5	1186.0	962.0	1184.5	863.5	1168.0	1166.0	1122.0	858.0	739.5
20	900.0	800.5	801.0	999.5	907.0	936.0	1263.5	1249.0	1196.5	1004.0	900.5
30	884.5	557.5	563.0	837.0	888.5	518.0	958.0	971.0	913.5	749.0	678.5
40	756.0	647.5	623.0	651.0	618.5	706.5	821.5	601.0	903.0	802.0	885.5
50	896.5	947.5	953.0	956.0	891.0	572.0	898.5	618.5	766.0	913.0	817.5
60	900.0	781.0	844.5	783.5	896.0	668.5	722.0	176.5	821.0	690.0	815.5
70	707.5	796.5	707.0	798.5	672.5	674.0	876.5	380.5	882.5	875.5	854.5
80	802.5	818.5	865.5	827.5	812.5	659.5	492.5	413.5	896.5	773.0	808.0
90	651.5	907.5	910.0	914.5	908.5	655.0	472.0	468.5	920.0	790.0	910.0
100	521.0	745.0	783.0	748.0	785.0	627.0	505.5	417.5	896.5	873.5	576.0
110	616.0	516.0	871.5	512.5	871.0	685.5	600.5	476.5	804.5	926.5	615.0
120	700.5	505.5	900.0	504.0	903.0	583.0	600.5	514.5	717.5	905.5	916.5
130	592.0	504.5	823.0	505.5	501.5	702.5	611.0	652.5	631.5	914.0	556.5
140	946.0	513.0	825.0	523.0	522.5		689.5	701.0	958.0	930.0	147.0
150	624.5	563.0	898.0	556.5	543.0		712.0	698.0	984.5	848.0	283.0
160	944.0		1089.0	1068.0	670.0		848.0	847.5	979.0	480.5	406.0
170	594.0		1168.5	1061.0	763.5		954.0	948.5	1130.5		
Grand Time(s)	83.5	80.0	83.5	83.5	83.5	70.0	83.5	83.5	83.5	85.0	85.0
Grand Mean Temp. (℃)	770.7	719.1	871.2	776.9	784.6	680.9	776.1	664.7	913.1	833.3	663.5

CONCLUSIONS

This work examines the ignition time of selected ceiling materials falling in the range of 70 s - 85 s. The maximum time of burning process completion is 85 s at 833.3°C and 633.5°C for sample 10 and asbestos, correspondingly, while the minimum time is 70 s at 680.9°C for sample 6. The high temperature recorded is a result of the heat generated by the coal. The latter represents the additional building material used to reinforce the ceiling sample.

Firemen are expected to carry out a rescue operation within 85 s. Their personal protective cover has to be examined for provision of fire retardancy aiming prolongation of the operation time.

Acknowledgements

The authors wish to acknowledge Covenant University for their partial sponsorship and contribution to the completion of this research paper.

REFERENCES

1. N. I. of S. and Technology, Fire compartment, 2013.
2. S. Ovosi, Preventing Disaster in Nigeria, 2017, http://www.gamji.com/article8000/news8296.htm.
3. B. Temi, Family Lose 3 Children To Lagos Fire Outbreak, Nigerian Monitor, Lagos, 2017.
4. A. Adekunle, A. Asuquo, N. Essang, I. Umanah, K. Ibe, B.A. Alo, Statistical Analysis of Electrical Fire Outbreaks in Buildings: Case Study of Lagos State, Nigeria, J. Sustain. Dev. Stud., 9, 1, 2016, 76-92.
5. Admin, Fire Outbreaks in Nigeria, The Tide, Bayelsa, 24-Dec-2010.
6. G. Havel, Construction Concern:Fire Behaviour in Buildings Part 1, Fire Engineering, 2017, www.fireengineering.com.
7. G. Havel, Construction Concerns: Fire Behavior in Buildings, Part 2, Fire Engineering, 2017.
8. D. Drysdale, An introduction To Fire Dynamics, John Wiley Sons., 1998.
9. P.A. Kittle, Flammability of Plastics & Polymers used as alternate Daily Covers," West Chester, 1993.
10. H. April, Aircraft Materials Fire Test Handbook, Springfield,Virginia, 2000.
11. C. Vogel, A. Mueller, D. Lehmann, F. Taeger, Characterization of the Burning Behaviour of Plastics by a New Method, v. 2012, May, 2012, 86-90.
12. C.J. Hilado, Flammability Handbook for Plastics, 5th ed., Basel, Technomic Publishing Company, 1998.
13. M.C. Onyeaju, E. Osarolube, E.O. Chukwuocha, C.E. Ekuma, G.A. Omasheye, Comparison of the Thermal Properties of Asbestos and Polyvinylchloride (PVC) Ceiling Sheets, Mater. Sci. Appl., vol. 3, 2012, 240-244.
14. N.F. Gesa, R.A. Atser, S.I. Aondoakaa, Investigation of the Thermal Insulation Properties of Selected Ceiling Materials used in Makurdi Metropolis (Benue State-Nigeria), Am. J. Eng. Res., 3, 11, 2014, 245-250.
15. E.B. Ettah, J.G. Egbe, S. A. Takim, U. P. Akpan, and E. B. Oyom, "Investigation of the Thermal Conductivity of Polyvinyl Chloride (Pvc) Ceiling Material Produced In Epz Calabar , For Application Tropical Climate Zones, J. Polym. Text. Eng., 3, 2, 2016, 34-38.
16. O.N. Nwoke, I.P. Okokpujie, S.C. Ekenyem, Investigation of Creep Responses of Selected Engineering Materials, Journal of Science, Engineering Development, Environmen and Technology (JOSEDET) 7, 1, 2017, 1-15.
17. J.O. Dirisu, A.A. Asere, J.A. Oyekunle, O.O. Ajayi, S.A. Afolalu, O.O. Joseph, A.A. Abioye, O. State, O. State, Comparison of the Elemental Structure and Emission Characteristics of Selected PVC and Non PVC Ceiling Materials Available in Nigerian Markets, International Journal of Applied Engineering Research, 12, 23, 2017, 13755-13758.
18. W. Conshohocken, ASTM D4477-16 Standard Specification for Rigid (Unplasticized) Poly(Vinyl Chloride) (PVC), PA, 2016, https://www.astm.org/Standards/D4477.htm.
19. A. Tewarson, Fire Science, Fire Sci., 10, 1992, 188-241.
20. L. Anthony, Plastics and the Environment, John Wiley Sons, 2003.
21. P. Philip, L. Fagbenle, Design of LEE'S Disc Electrical Method for Determining Thermal Conductivity of a Poor Conductor in The form of a Flat DISC, Int. J. Innov. Sci. Res., 9, 2, 2014, 335-343.
22. E. Rathakrishn, Elements of Heat Transfer. Boca Rato, London: CRC Press Taylor and Francis Group, 2012.

23. J.-C. Han, Analytical Heat Transfer. Broken Sound Parkway NW, CRC Press Taylor and Francis Group, 2012.
24. D. Madrzykowski, Fire Dynamics: The science of fire fighting, Int. fire Serv. J. Leadersh. Manag., 7, 2013, 1-76.
25. A. Azhakesan, T.J. Shields, G.W.H. Silcock, Developments on the Fire Propagation Test, Dev. Fire Propag. Test. Fire Saf. Sci., 4, 2012, 349-360.
26. RRC International, Principle of fire and explosion, RRC International, http://www.rrc.co.ae/media/299612/IFC1 SAMPLE MATERIAL.pdf.
27. J.O. Dirisu, S.O. Oyedepo, O.S.I. Fayomi, I.P. Okokpujie, A.A. Asere, J.A. Oyekunle, S. A. Afolalu, A.A. Abioye, Effects of Emission Characteristics on Elemental Composition of Selected PVC Ceiling Materials, Materials Focus, 7, 2018, 571-577, (www.aspbs.com/mat)
28. S.L. Quarles, Fire Ratings for Construction Materials, 2013, http://articles.extension.org/pages/31039/fire-ratings-for-construction-materials.
29. R. Solomon, National Fire Protection Association Report, Underwriters Laboratories Inc., 333 Pfingsten Road, Northbrook, 2016.
30. Singapore Quality Class, The use of combustible materials for internal partitions and ceilings , roof covering , and wall/ceiling finishes, Singapore, 2002.
31. O. Mimiko, National building code, Federal Republic of Nigeria, Abuja, Nigeria, 2006.