The thermal efficiency of aluminum roofing sheets lined with plywood and common ceilings in tropical buildings in Nigeria

J. B. Taiwo[1], B. I. O. Dahunsi[2]
[1]Department of Architecture University of Ibadan, Nigeria
Jb.taiwo@ui.edu.ng
[2]Department of Civil Engineering University of Ibadan.
biodahunsi@ui.edu.ng

Abstract: ***The main source of indoor discomfort has been identified as high solar radiation entering through the roofs and ceiling layout. The synergistic combination of ceiling underlay and roofing sheet was critical in controlling internal heat imbalance in the tropics. Hence, this works examined the impact of lined and non-lined aluminium roofing sheet in the tropical buildings, Ibadan Nigeria. Three prototype miniature buildings oriented north south were roofed with plywood-lined aluminum roofing sheets (PLARS) and non-lined aluminium roofing sheet (NARS) configured against some common ceiling underlay at various angles of 30, 45, and 60, respectively. Using a multichannel data logger, daily temperatures were collected for six months at 30-minute intervals. Data were analysed using descriptive statistics and ANOVA at $\alpha_{0.05}$. The findings showed that as configuration angle increases, the temperature of the Sampled Ceiling Materials (SCM) and sampled roofing materials (SRM) decreases. The average temperature at 30, 45, and 60°, for 6 p.m. and 10 p.m. in PLAR was 37.04-29.74, 35.5-28.66, 31.02-28.64°, showing a downward trend in temperature as the sunset approaches. Implies a conducive indoor space for the inhabitant during the night. While the NARS was 36.97-29.7, 38.72-30.16, 37.82-29.58°, implies a slightly higher air temperature at the twilight. However, the highest coefficient of correlation (R^2 = 0.95, 0.90) for PLAR and NARS obtained. The angles 30, 45, and 60 gave the Optimum Comfortability Roof (OCR) between 22 and 29°, based on the ASHRAE standard.***

Keywords: Performance, Configurations, Angles, Tropical.

1. Introduction

The building's orientation played a significant role in ensuring comfortable indoor conditions. Bekkouche *et al.* (2013) provide valuable insights into the role of building orientation in passive solar heating and cooling. By strategically orienting a building, architects and designers can leverage the sun's energy to enhance indoor comfort and reduce reliance on mechanical heating and cooling systems. During colder seasons, proper orientation can maximise solar heat gain, helping to naturally warm the interior spaces. Conversely, in warmer seasons, thoughtful orientation can minimise solar heat gain, thereby reducing the need for air conditioning and keeping indoor temperatures comfortable.

The arrangement of the roof also plays a crucial role in this process. By incorporating features such as overhangs or shading devices, designers can control the amount of sunlight that penetrates the building, further optimising its thermal performance.

Ultimately, building orientation is a key consideration in sustainable design, as it can significantly impact energy consumption, indoor comfort, and overall building performance. By carefully aligning buildings with the sun's path and implementing appropriate design strategies, architects can create spaces that are both environmentally friendly and comfortable for occupants.

According to Albatayneh *et al.* (2018), maintaining proper building orientation can significantly reduce energy costs and ensure indoor comfort by optimising sunlight exposure to specific interior areas throughout the day. Meanwhile, Cakir (2006) emphasised that a combination of good orientation and high-quality roofing materials enhances a building's resilience to external factors. Akshaya *et al.* (2017) proposed an optimal building orientation of 180 degrees to minimise solar heat transmission into interior spaces, thereby reducing the load on air conditioning systems by allowing sunlight into the space during the morning hours. However, in tropical regions, building orientation and design play a crucial role in achieving indoor thermal comfort. Bekkouche *et al* (2013), also recommended a building orientation of 90 degrees to achieve a 6:30 decrease in cooling consumption.

Throughout history, several methods have been utilised to enhance a building's thermal comfort. One traditional approach involves designing structures to maximise natural air circulation by strategically positioning openings. Additionally, mechanical solutions such as air conditioning have become prevalent, albeit contributing significantly to residential energy consumption, estimated between 30% to 75% (Cakir, 2006; Onyenokporo and Ochedi, 2019). Presently, architects and engineers are exploring roofing materials and ceiling configurations to achieve optimal interior thermal comfort. These innovations aim to reduce reliance on energy-intensive cooling systems while ensuring a comfortable indoor environment. Hence, this research is aim at establish thermal efficiency between plywood-lined aluminium roofing sheet and non-lined aluminium roofing sheet against common underlay ceilings in the tropical city of Ibadan, Nigeria.

2. Building Orientation and its Impact on the Internal Ambient

Building orientation stands as a pivotal sustainable strategy and passive approach to enhancing interior comfort in tropical constructions. This endeavor not only contributes to the physical and mental well-being of building occupants but also augments indoor environmental quality. As highlighted by Shivani and Vignesh (2021), the orientation of a building exerts significant influence on factors such as energy consumption, indoor environmental quality, and occupant satisfaction. It serves as a fundamental criterion for site planning, aiding in the mitigation of adverse effects of natural climatic elements such as solar radiation, ventilation, lighting, and noise, as noted by Alisha (2020). Furthermore, John (2017), corroborates that a north-south orientation proves advantageous for tropical structures, facilitating the capture of cooling breezes while minimising excessive sunlight exposure, thus averting overheating issues.

The lack of adherence to the north-south orientation in many Nigerian buildings has been noted to escalate the demand for energy used in interior cooling (Odunfa *et al.,* 2013). In contrast to mechanical cooling methods that contribute to air and noise pollution as well as greenhouse gas emissions, Nwofe (2014), suggests that Nigeria requires climate-responsive sustainable construction practices and roofing materials to foster a more comfortable indoor environment. Proper building orientation ensures an interior temperature that is both cost-effective and efficient. Buildings with correct orientation are inherently energy-efficient, requiring less energy to maintain thermal comfort, as highlighted by Pai and Siddhartha (2015). To establish this model, the research will adopt the two by five matrix theory, employing two roofing sheets configured against five different ceiling underlays. This approach aims to explore and optimise the combination of roofing materials and ceiling configurations to enhance interior comfort and energy efficiency in Nigerian buildings.

As shown in Figure1, this study was conducted in Ibadan, Oyo State, in the southwest region of the country, which is situated in low latitudes 7° 3N to 7° 4N and longitudes 3° 8 to 3° 9E of Nigeria. The influence of both plywood-lined aluminium roofing sheet and ordinary aluminium roofing sheet versus five (5) common underlay ceiling configurations that are frequently utilised in residential buildings in this area was the main focus of the study.

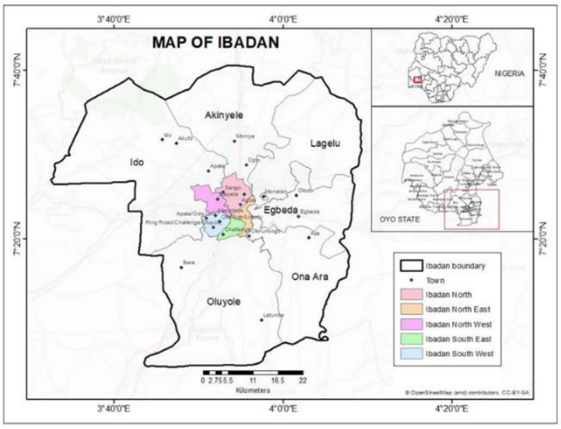


Figure 1: Map of the study area

3. Materials And Method

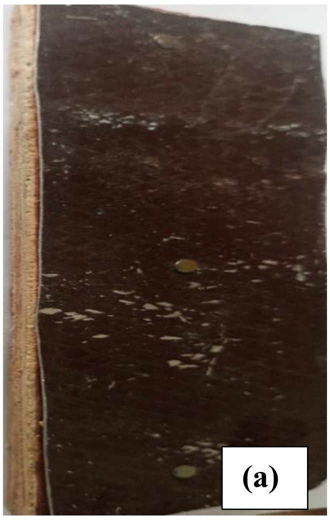
3.1. Materials

The study employed plywood-lined aluminium roofing sheet (PLARS) and non-lined aluminum roofing sheet (NARS) in combination with various Selected Ceiling Materials (SCM) including polyvinyl chloride (PVC), asbestos (ASB), plaster of Paris (POP), gypsum (GYP), and plywood (PLW), as depicted in Plates 1(a) to (h). All five selected ceiling samples were paired with the PLAR and NARS roofing samples. The materials were cut into appropriate sizes using a handsaw, steel ruler for measurement, and nails for the assembly of miniature building prototypes. Temperature measurements within the interior part of the prototype models were recorded daily using a timer and multi-channel data recorder.

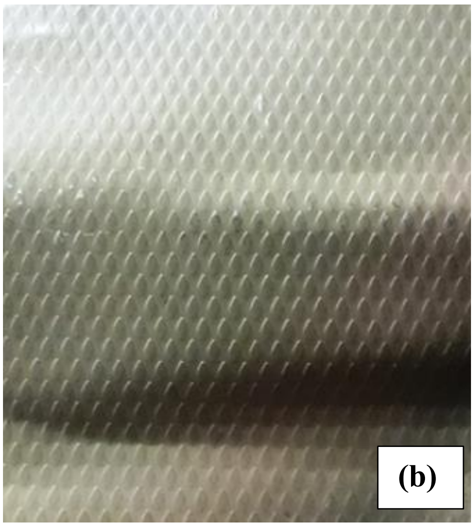
3.2. Method

Three prototype miniature models were constructed and roofed using Plywood-lined Aluminum Roofing Sheets (PLARS) and Non-lined Aluminum Roofing Sheets (NARS), configured with five distinct Selected Ceiling Materials (SCM) at angles of 30, 45, and 60 degrees, all oriented north-south as shown in Plate 2 and 3. The models were built using plywood boards, forming closed box buildings with dimensions of 3000 mm (3m) in length and 1800 mm (1.8 m) in height. To minimise heat loss through window and door openings, the models were made airtight with no openings. Plate 2 and 3 illustrates the field configurations set up at angles 30, 45, and 60 for stone-coated roofs.

Temperature readings were conducted daily at 30-minute intervals from 8:45 a.m. to 9:45 p.m. Using a 4-channel multi-channel recorder, concurrent temperature readings were taken. Channels 1 and 2 recorded the temperature at the roofing sheet and the temperature inside the roof air space, respectively, while channels 3 and 4 recorded the temperature on the ceiling and the temperature of the ambient air outside. This field study was carried out from September 2022 to March 2023.

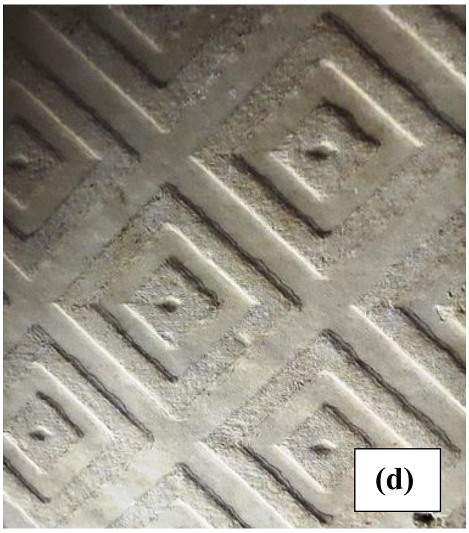


(a) Plywood-lined Aluminium roofing sheet



(b) Non-lined Aluminium roofing sheet

(c) Polyvinyl chloride PVC



(d) Asbestos ceiling ASB

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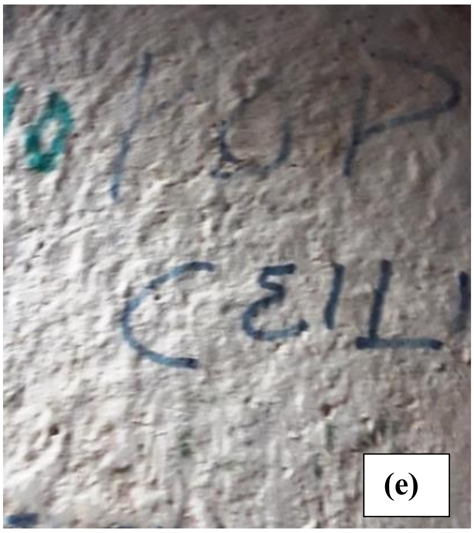
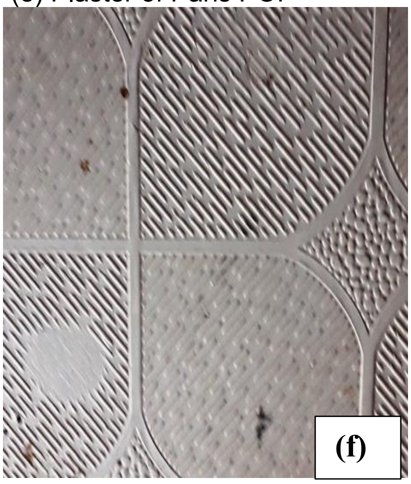


(e) Plaster of Paris POP



(f) Gypsum ceiling

(g) Plywood ceiling board (PCB)

(h) multichannel data logger

Plate 2: Experimental set up for plywood-lined aluminium roofing sheet with selected ceiling materials

Plate 3: Experimental set up for aluminium roofing sheet with selected ceiling materials

4. Results And Discussion

Figure 1 shows the trend of variation of air temperature for different combinations and angles. It is clearly visible from the figure that air temperatures on the sample roofing sheet was high across all the angle irrespective of the combination. This implied that aluminium roofing sheet are good conductor of heat.

Meanwhile, the air temperature decreases in the roof air space across the combination due to the lining effect of plywood on the sample sheet. This show that plywood materials is an insulator of heat. Moreso, the plywood acting as composite to the aluminium increases the thermal mass, absorbing more heat during the day and releasing it slowly, thereby, stabilising indoor air temperature.

The figure also shows that, there is decrease in air temperature on all the selected ceiling materials at different combinations, especially from the 4:30 p m in the evening to the late hour of the day, causing a relative cool air temperature within the space.

However, from the overall observation, we can deduce that the air temperature was generally low at 45- and 60-degrees configurations for the combination of PLAR against PVC and POP. This has practical implications across regions or zones in Nigeria as the difference in angles of inclination can affect the utilisation of the roof types based on the temperature differences across the geo-political zones in Nigeria. This finding aligns with those of Jayasingbe, *et al.,* (2003), Melisa, *et al.,* (2016) and Cobo and Montoya (2021) that, in hot climate zones such as Nigeria, material, insulation, surface colour and effect of roof orientation directly influence the maximum interior temperature of housing solutions.

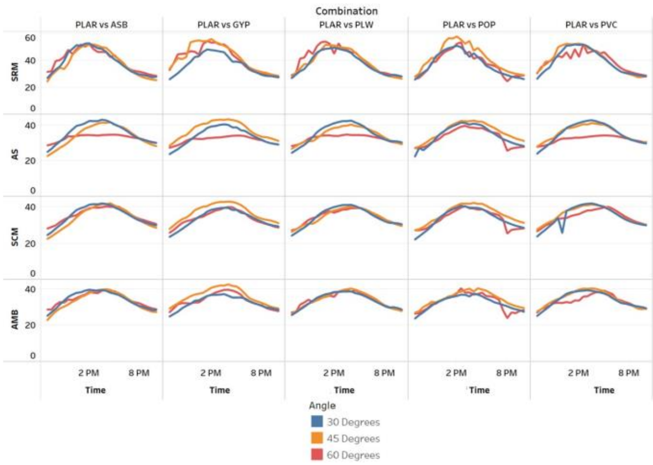


Figure 1: Daily temperature variation for different angles with respect to different combinations and materials

Apparently, Figure 2 shows the trend of air temperature variations for different combinations and angles. It was noted from the figure that ambient air temperature was high on the roofing sheet across all combinations, especially from 11: 30 a m to 3: 30 p m, during the peak hour of the day. Similarly, there is increase in the air temperature within the roof air space because there was no lining to insulate the influx of heat into the roof causing high air temperature saturation within the roof.

However, the ambient air temperature and the selected ceiling temperature SCM had similar patterns for the three angles of configuration. The figure further revealed that there is slight increase in the ambient air temperature under this configuration during the night period.

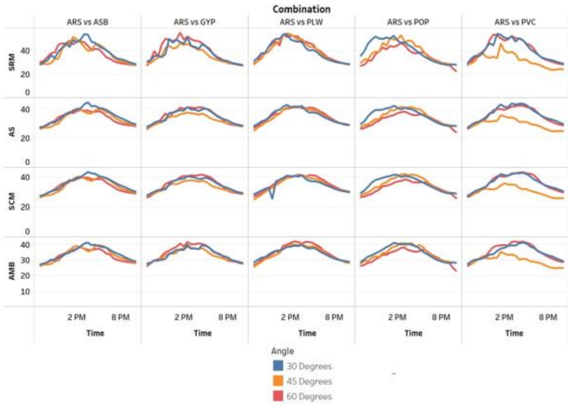


Figure 2: Daily temperature variation for different angles with respect to different combinations and materials

4.1 Statistical analysis of temperature dynamics between PLAR and Selected Ceiling Materials (SCM)

Table 1 shows that temperature was generally higher at PLAR compared to the air space (AS), SCM and ambient AMB. Also, temperature deviated from the average for PLAR compared to others.

Table 1: Summary of temperature for different configurations

		Temperature (^{0}C)			Std.
	N	Min	Max	Mean	Deviation
SRM	405	22.5	55.2	38.511	8.1377
AS	405	24.2	44.8	34.673	4.8317
SCM	405	24.9	43.4	34.641	4.6392
AMB	405	23.1	42.1	33.830	4.4412
Valid N (listwise)	405				

Meanwhile, Table 2 summarises the different temperatures on the PLAR in comparison to the air space, SCM and ambient, based on different angles of roof configurations. The table shows that the average temperature was highest in roofing material, air space and ceiling material for roofing configuration with angle 30^0 in comparison to angles 45^0 and 60^0. Although, it was reported by Alcivar, Ramos, and Velez (2022) that the best thermal behaviour inside the house is from the pitched roof orienting towards the west with inclination angles of 20°. However, the

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present study showed that the best optimum angle of inclination ranges from 30° to 60°.

The statistical analysis was used to predict the temperature of ceiling materials based on ambient temperature and time (GMT) for the different combinations for PLARS

A mathematical model was formulated, as represented in Equation 1 to predict the temperature of the ceiling materials at a given time with respect to the angles of inclinations.

$$Y_i = \beta_0 + \beta_1 X_{i1} + \beta_2 X_{i2} + \beta_3 X_{i3} \quad \ldots \quad 1$$

where Y_i is Temperature of Ceiling Material, X_1 is Time, X_2 is Ambient Temperature, X_3 is Angle of Configuration; β_0 is the intercept of the fit, while $\beta_1 - \beta_3$ are the coefficient of the independent variables.

Table 2: Summary of linear regression model parameters

Dep. Variable:	SCM	R-Squared:	0.949
Model:	OLS	Adj. R-Squared:	0.949
Method:	Least Squares	F-Statistic:	2511.
Date:	Fri, 24 Feb. 2023	Prob (F-Statistic):	1.84e-259
Time:	13:28:03	Log-Likelihood:	-603.25
No. Observations:	405	AIC:	1215.
Df. Residuals:	401	BIC:	1231.
Df. Model:	3		
Covariance Type:	Nonrobust		

	Coef	std err	T	p>|t|	[0.025	0.975]
Intercept	-5.7487	0.527	-10.918	0.000	-6.784	-4.714
Time	0.2108	0.014	15.326	0.000	0.184	0.238
AMB	1.1078	0.013	85.509	0.000	1.082	1.133
ANGLE	-0.0062	0.004	-1.414	0.158	-0.015	0.002

Omnibus:	254.806	Durbin-Watson:	0.991
Prob (Omnibus):	0.000	Jarque-Bera (JB):	8525.618
Skew:	-2.098	Prob (JB):	0.00
Kurtosis:	25.082	Cond. No.	582.

After fitting the factors and the temperature in a regression model and deriving their respective coefficient. Equation 2 summarised their relationship and it is presented below:

$$SCM_y = -5.7487 + 0.2108X_1 + 1.1078X_2 - 0.0062X_3 \quad \ldots \quad 2$$

The model's variables coefficient values were used for assessing the impacts of the factors on the temperature of the ceiling materials irrespective of the selected combinations as presented in Table 2.

From Table 2, the coefficient of the intercept was -5.7487 and this implies that there is a decrease in the unit temperature of the ceiling material as the other variables not included in the model increases while the other independent variables are held constant. It also shows that the coefficient of Time is 0.2108, there is an increase in the unit temperature of the ceiling material as time increases from 9:00 to 24:00 while the other variables are held constant.

It also shows that the ambient (AMB) coefficient was 1.1078 and this signifies an increase in the unit temperature of the ceiling material as the ambient temperature increases while the other variables are held constant. Further observation from the table shows that the configuration angle of coefficient was -0.0062, which signifies there is a decrease in the unit temperature of the ceiling material for every increase in the angle of configuration in the order of 30^0, 45^0 and 60^0 while other variables are held constant. The coefficient of p values shows that the coefficients are statistically significantly different from zero since all the values are less than 0.05 except for the angle of configuration. This implies that the angle of configuration does not significantly affect the temperature of air space based on the combined SRM and SCM.

The Coefficient of Determination (R^2) depicted in the table had a value of 0.965 and it shows the measure of the overall strength of the model. Since the R^2 is approximately 1, it can be concluded that the model is adequate in determining the temperature of ceiling material based on the experimentally observed independent variables. There are indications also that these factors are not the only factors responsible for the thermal conditions of the ceiling material.

The table further shows that null hypothesis F test proved that all the model coefficients were equal to zero. Since the p value for the F test was <0.00, which is less than 0.05, it can be inferred that all the coefficients are zero; this implies that there is a relationship among the selected independent variables and the temperature of the ceiling material.

4.2 Statistical analysis of temperature dynamics between NARS and SCM

Table 3 shows that temperature was generally higher at NARS compared to that for AS, SCM and ambient AMB. Also, temperature deviated from the average for NARS compared to the others.

Table 3: Summary of temperature for different configurations

	N	Temperature (^{0}C) Min	Max	Mean	Std. Deviation
SRM	405	22.4	57.9	39.589	8.7637
AS	405	22.4	43.3	34.374	4.6638
SCM	405	22.1	43.0	34.752	4.7795
AMB	405	22.9	42.6	33.879	4.1422
Valid N (listwise)	405				

To predict the temperature of Selected Ceiling Material (SCM) based on ambient temperature and time (GMT) for the different combinations for NARS

After fitting the factors and the temperature in a regression model and deriving their respective coefficient, the relationship was summed up in Equation 3 as presented below:

SCM = -0.644833 + 0.081303X1 + 1.019626X2 - 0.010241X3 … 3

The model's variables coefficients values used for assessing the impact of the factors on temperature of the ceiling materials, irrespective of the selected combinations, as presented in Table 4

Table 4: Summary of linear regression model parameters

Dep. Variable:	SRM	R-Squared:	0.953
Model:	OLS	Adj. R-Squared:	0.953
Method:	Least Squares	F-Statistic:	2728.
Date:	Sat, 18 Feb. 2023	Prob (F-Statistic):	2.62e-266
Time:	17:37:23	Log-Likelihood:	-575.26
No. Observations:	405	AIC:	1159.
Df. Residuals:	401	BIC:	1175.
Df. Model:	3		
Covariance Type:	Nonrobust		

	Coef	std err	t	P>|t|	[0.025	0.975]
Intercept	-0.6448	0.482	-1.339	0.181	-1.592	0.302
Time	0.0813	0.013	6.326	0.000	0.056	0.107
AMB	1.0196	0.011	90.310	0.000	0.997	1.042
ANGLE	-0.0102	0.004	-2.507	0.013	-0.018	-0.002

Omnibus:	3.119	Durbin-Watson:	1.072
Prob (Omnibus):	0.210	Jarque-Bera (JB):	1.3237 .315
Skew:	-0.020	Prob (JB):	0.00
Kurtosis:	3.455	Cond. No.	570.

From Table 4, the intercept coefficient was -0.644833 and this implies a unit temperature decrease of the ceiling material for every increase in other variables that are not included in the model while the other independent variables are held constant. Further observations showed that the coefficient of Time was 0.081303; this means that unit temperature of ceiling materials decreases as time increases from 9:00 to 24:00 while the other variables are held constant.

It also shows that the ambient temperature coefficient was 1.019626; it implies that there is an increase in the unit temperature of the ceiling materials as the ambient temperature increases, while other variables are held constant. This is in tandem with the finding in Lawal, Akinpade and Makinde (2017). A further observation of the table shows that the configuration angle coefficient was -0.010241; this signifies a decrease in the unit temperature of the ceiling materials for every increase in the angle of configuration in the order of 30^0, 45^0 and 60^0, while the other variables remain constant. The coefficient of p values shows that the coefficients were statistically significantly different from zero since all the values were less than 0.05, except for the intercept. This implies that the other factors that were not considered in developing the model do not significantly affect the temperature of air space based on the combined SRM and SCM.

The Coefficient of Determination (R^2) depicted in the table had a value of 0.953 that showed the measure of the overall strength of the model. Since the R^2 was approximately 1, it can be concluded that the model was adequate in determining the temperature of ceiling materials based on the experimentally observed independent variables. There are indications also that these factors are not the only factors responsible for the thermal conditions of the ceiling materials.

The table further shows that the null hypothesis F test affirmed that all the model coefficients were equal to zero. Since the p value for the F test was <0.00 and it was less than 0.05, the conclusion is that not all the coefficients are equal to zero, this means there is a relationship among the selected independent variables and the temperature of the ceiling materials.

5. Conclusion

This paper presents the results of the study on thermal efficiency of the plywood-lined aluminium roofing sheet and non-lined aluminium roofing sheet against some selected ceiling materials conducted in Ibadan, Nigeria, evaluating their effectiveness against some common ceilings. This project aims to evaluate the impact of the sample roofing materials, the angles of inclinations and the selected ceilings on indoor temperature, which will guarantee a comfortable interior ambient temperature habitable for humanity.

In order to ensure a conducive internal space, this research has established that the higher the angle of inclination, the lower the roof temperature and the lower the temperature of the corresponding indoor spaces. The result also shows that aluminium roofing sheets lined with plywood offer superior thermal efficiency in the tropical buildings in Nigeria. Their high reflective, combined with the insulating property of plywood, gave a greater thermal mass which make them more efficient in reducing heat gain and maintaining comfortable indoor temperatures. The result from combinations also offers adequate configuration for this tropical zone, particularly true for the roof configuration between PLAR, and POP, or PVC, at an angle of 45 to 60°.

As a result, it has been demonstrated that the innovative roof configuration that meets ISO 7730 Standard requirements for maximum comfortability roof (OCR) is also possible.

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