INTERNATIONAL JOURNAL OF
ENERGY AND ENVIRONMENT

Volume 5, Issue 6, 2014 pp.709-716

Journal homepage: www.IJEE.IEEFoundation.org

Thermal insulation capacity of roofing materials under changing climate conditions of Sub Saharan regions of Africa

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Abstract

Climate change is affecting human indoor thermal comfort. Human habitat roof's thermal insulation capacity may play key role in reducing the discomfort resulting from climate change. In the present study, six roof materials are analyzed for their thermal insulation capacity: aluminum-iron (Al-Fe) sheet, Al-Fe sheet with outer face white painted, Al-Fe sheet with various straw thick, white tile, red tile and gray tile. Solar radiations, ambient temperature, wind speed, roof inner and indoor temperatures were daily measured during April and June. Measured roof inner wall temperatures for each type of material agreed with the model set forth. The indoor temperature showed, under the same atmospheric conditions, Al-Fe sheet at a maximum of 51.4°C ; Al-Fe sheet with outer face white paint at 40.3°C; Al-Fe sheet with 3cm thick of straw at 41.2°C; and Al-Fe with 6cm thick of straw at 36.8°C, making the latter the better roof at day time. For the inner wall temperatures of the roof without ceilings, Al-Fe sheet has a maximum at 73°C; Al-Fe sheet with outer wall white paint at 48.1°C; Al-Fe sheet with 3cm straw thick at 45.2°C; and Al-Fe with 6cm straw thick at 37.9°C, red tile at 51.3°C; white tile at 41.6°C and grey tile at 51.6°C. This study enlightens the change that can be made on the traditional roof to improve indoor thermal comfort in changing climate conditions.

Keywords: Climate change; Indoor thermal comfort; Roof materials; Solar radiation; Thermal insulation.

1. Introduction

The thermal behavior of a building depends on the construction materials used to build it. Recently, a study related to construction materials and thermal comfort in hot zones of Cameroon dealt with local materials such as woods, clay bloc, compared to cement bloc [1]. Obviously, the study was about the building's wall materials. Wall materials play key role in a building comfort. However, a building roof, the one receiving the most direct solar radiation, contributes a lot to the heat in the building. According to a study, the heat contribution from roof to the overall heat of a room is about 70% depending on the type of the material [2]. Various roof materials are in use, depending on climatic conditions, people's desire, and finance. The primary concern in selecting roof material is its durability [3]. Most of homeowners select the roof material based on how resistant to weather conditions it may be. However, other homeowners look for roof material to match their homes where aesthetic is the focus. Other non negligible points are the availability of installation technique, the maintenance effort and the ease to repair.

A human habitat roof plays keys role in both protecting against rain, wind, sun and others [4] and providing certain comfort [5]. In Sub-Sahara Africa, traditional and modern roofs are in use depending on the areas (cities or villages), and the financial situation.

Traditional roofs made of local materials, even though proven to be thermally comfortable to some extends suffer of a relatively short life which forces the users to reconstruct basically almost after every rainy season. [4, 5].

To efficiently address the issues of house roof frequent wear, modern roofs are developed even in remote areas of Sub-Saharan African Countries [4]. The modern roofs may consist of metal sheets, reinforced concrete, for the economically sufficient people. The less fortunate will use metal sheets made of galvanized iron, aluminum, and zinc. But in the relatively wet zones, under intensive rainfalls, high relative humidity, and coastal zones of Sub-Sahara Africa, even those roofs suffer frequent rusting and need to be renewed very often. Some alternatives are found such as painting the galvanized iron with anti-corrosive substances, or using various types of tile, etc.

However, as the issues of frequent roof wear seem to be resolved, everything being equal elsewhere, users face another crucial issue: the thermal comfort in modern roof houses at low cost under changing climate [6].

Various studies related to the electric consumption and the perceptions of the indoor comfort by inhabitants in low income cities such as Mexicali, in Mexico, other 11 countries and 36 sustainable and institutional buildings were undertaken [7]. Links were established with electric consumption and the perceptions of the indoor comfort and building design and building material [8].

However, few studies deal with the specific thermal contribution of the roof to the house.

Recently, a model has been developed to measure, taking into account the climate parameters, the heat flux transfer to the room through its roof [4].

The present study is a comparative analysis of the thermal insulation capacity of various types of roof materials used in Sub-Sahara African regions in order to propose the thermally efficient roof material that would contribute in low heat transfer to room, thus contributing to climate change adaptation and reducing climate change impact on people of those regions.

2. Method and material

2.1 Study site characteristics

The method and the material employed in the present study have been extensively described elsewhere [4]. Succinctly, the study was conducted near the University of Ougadougou (Burkina Faso), a city located in the Soudano-Sahelian zone. The climate of the zone is characterized by a unimodal precipitation regime, with a rainfall of about 600 mm per year. The rainy season stretches from mid- May to mid-October, with an average temperature of 30°C. June, July, August, and September totalize more than 80 % of the seasonal rainfall. The cold season runs from December to January, with a minimum temperature of 19°C. The maximum temperature during the hot season, which runs from March to May, can reach 45°C. Relative air humidity varies from 20% in March during dry season to 80% in August during rainy season with a mean of 49% [9].

The geographic characteristics of the study site are: 12º22´46.19"N, 1º29´58.77"W.

2.2 Material

Experimental boxes made of wood on top of which the roofing material is placed to serve as roof were used. The boxes were put at a height of 1m above the ground at points where no shade influence from building, trees or other affects the measurements.

The galvanized iron sheet produced by Qingdao Hengcheng Steel Co., Ltd. (Thickness: 0.5mm, length: 1m, width: 1m), was purchased at Ouagadougou’s market place. Straw was harvested on the campus field and dried for thirty days prior to the experimentation. The white paint coat was uniformly applied on the galvanized iron sheet; red, gray, and white tile samples were obtained from a roof promoter in Ouagadougou.

Solar radiations were measured using a CMP- pyranometer placed close to the box at the same height from the ground.
Temperature gauges were positioned for the ambient temperature, the room temperature, the external and internal roof wall temperatures, etc. The ambient temperature is measured at a height of 5m above the ground. The gauges were electrically connected to the temperature sensor that gives a simultaneous read-out of all temperatures with decimal absolute error.
A rotating cup anemometer was employed to measure the wind speed.

3. Results and discussion

The atmospheric parameters such as solar irradiation, wind speed, and ambient temperature were recorded on clear sky days of April and June (Figure 1). At night time, between 7:00PM and 7:00AM while solar irradiation is zero, roof temperatures are not similar to the ambient ones to reflect the nullity of solar energy (results not shown). This is basically due not only to the thermal inertia that characterizes some roof materials, but also the fact that there was no openings made in the experimental boxes to serve as window through which heat could be evacuated to the ambient. Thus, it is solely reported in the present study data for which the solar radiation is not null so that solar influence on the roof temperature can be seen for proper analysis.

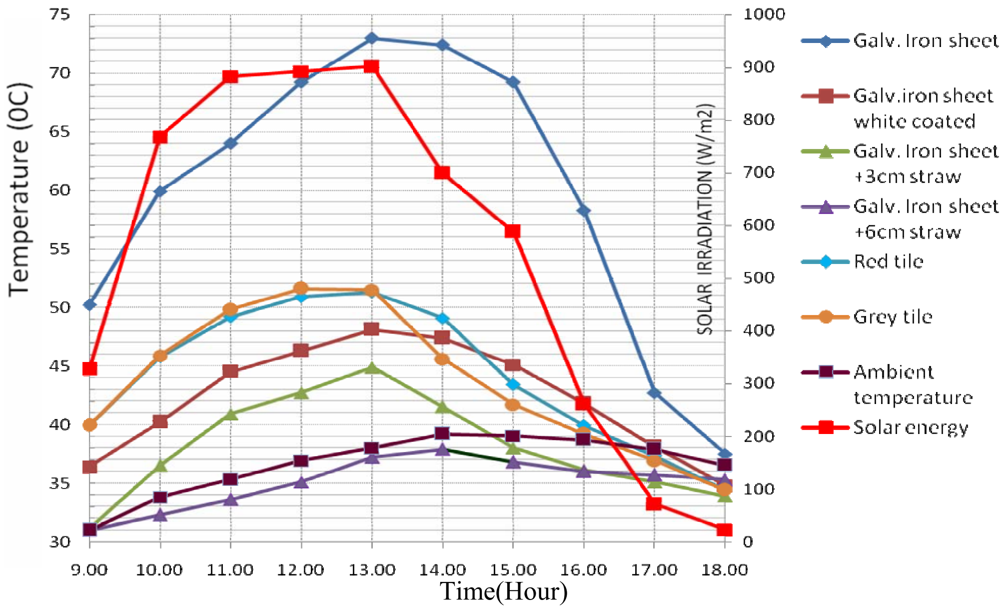

Figure 1. Hourly solar radiation was measured and represented in red on the second vertical axis; roof inner wall temperatures for each roof material were simultaneously recorded. Al-Fe sheet roof appears to be the thermally unfavorable roof material followed by red and grey tiles, and then comes the Al-Fe white painted. Increasing straw thick on the Al-Fe considerably reduces heat transfer to the room

Burkina Faso, the country where the study was conducted, Mali, Niger, the northern part of Benin, Togo and Nigeria in West Africa are located in the bands between 15^o and 35^o north and south around the earth where the greatest amount of solar energy is received [10, 11]. The direct solar energy recorded in the present study matches the one observed in various cities of Nigeria [12] and elsewhere [13-15].
Table 1 reports on the daytime temperatures of the inner wall of various roof materials. All the roof materials have their maximum temperature towards 1:00 PM, which corresponds to the time the solar radiation is approximately at its maximum (Table 2). The galvanized aluminum-iron sheet (Al-Fe) reached the highest temperature of about 73°C, way above the ambient temperature of 39°C. Among all the roof materials, only Al-Fe+6cm provides temperature inferior to the ambient one all day long. Second to the Al-Fe + 6cm, in terms of low temperature roof material, is the Al-Fe + 3cm straw thick. Therefore, it can be concluded that the thicker the straw, the lower the temperature. In fact, house roofs in villages are made solely with straw which thick can reach 60cm. The experiences show that the room temperatures in such houses are below the atmospheric one. However, the thick of the straw is not only for low room temperature but also to render the roof waterproof. Roof waterproofing is the first intent of

great straw thick. The present study has the merit of showing that the roof thick, when straw is used, contributes to lowering room temperature.

Table 1. Ambient temperature, Galvanized aluminum-iron (Al-Fe) sheet, Al-Fe sheet +3cm straw, Al-Fe sheet+6cm straw, Red tile, and Grey tile roof inner wall temperatures in °C are recorded on an hourly basis

Time	Ambient Temp.	Al-Fe	Al-Fe white painted	Al-Fe +3cm 3cm st straw	Al-Fe +6cm straw	Red Tile	Grey Tile
09:00	31	50,2	36,4	31,1	31	39,9	39,9
10:00	33,8	59,9	40,2	36,5	32,3	45,8	45,9
11:00	35,3	64	44,5	40,9	33,6	49,2	49,8
12:00	36,9	69,2	46,3	42,7	35,1	50,9	51,6
13:00	38	73	48,1	44,9	37,2	51,3	51,5
14:00	39,2	72,4	47,4	41,5	37,9	49,1	45,6
15:00	39	69,2	45,1	38	36,8	43,4	41,7
16:00	38,7	58,3	41,8	36,1	36	39,9	39,2
17:00	37,9	42,7	38,1	35,1	35,7	37,3	36,9
18:00	36,5	37,5	34,8	33,9	35,3	34,4	34,4

Table 2. Roof material thermal and physical properties

Roof material	Absorp. coef ε_{pa}	Int. emis. coef ε_i	Ext. emis. coef ε_e	Therm. conduct. $\lambda(w/m^2)$	Roof thick e (mm)
Al-Fe	0.8	0.3	0.3	45	0.5
Al-Fe white coat	0.3	0.3	0.9	45	0.6
Al-Fe + straw	0.7	0.3	0.9	0.045	30-60
Red tile	0.68	0.9	0.9	0.5	8
Grey tile	0.58	0.85	0.85	0,5	8
White tile	0.3	0.9	0.9	0.5	8

The third roof material that shows low roof temperature among the roof materials employed is the Al-Fe white painted. It is common to people living in coastal zone or wet atmospheric conditions to use anti corrosive materials to paint their house roof. The goal is to avoid a fast rusting of the sheet. In our experiment, we have had a close look at the impact of a white coating over the galvanized sheet on the roof temperature. Amazingly, the white painted roof shows temperature distribution in a Gaussian shape comparable to the shape previously obtained [4]. The temperature behavior observed is a gain of about 25°C just by painting white the Al-Fe. The reduced comfort cost with roof material had been discussed elsewhere. In the Baltimore, a significant summer cooling cost reduction along with health benefits by liquid coating of roof (roof painting) is reported [16]. White or light-colored roofs can cut-off air-conditioning costs by up to 20 percent and even lower indoor temperatures inside buildings without air conditioning. In Washington, areas where cool roofs were installed, heat-related deaths declined by 6 percent to 7 percent [16].

In the present study, at sun set, between 5:00PM and 6:00 PM, where the solar radiation is almost zero, it can be noticed that all of the roof materials, except for the Al-Fe, cools down more rapidly than the atmosphere. However, between 4:00PM and 6:00 PM, Al-Fe + 6 cm exhibit higher temperatures than Al-Fe+3cm. This means that the former roof cools down more slowly than the later. Again, the thermal inertia due to the thick of the roof material is at the origin of this observation. Heat evacuation appears to be easier with smaller straw thick.

Red tile and grey tile exhibit the same temperature behaviors between 9:00AM and 1:00PM. However, from 1:00PM to 6:00PM, grey tile roof shows temperatures lower than those from the red tile. This can be explained by the absorption of wave lengths that is color dependent. In the present study, grey tile absorbs solar radiation less than the red tile. From the thermal insulation stand point, the galvanized Al-Fe sheet appears to be the roof material that transfers more heat to a room. A maximum temperature of 73°C was attained, thermally making this type of roof material the most undesirable one. The high

absorption coefficient of the Al-Fe material compared to the other roof materials explains this observation. However, when slight modifications such as white painting or using various straws thick are made on the Al-Fe material, this greatly improves the thermal behavior of the Al-Fe.
It is expected that the room temperatures under various roof materials be lower than their respective roof temperatures. Curves from Figure 2 give the Al-Fe room temperature to vary from 40^o C by 9:00 AM to a maximum of 57^{o}C in the early afternoon. Rooms under grey and red tiles have the same temperature behaviors, their temperatures varying approximately from 37^{o}C in the morning to a maximum of 52^{o}C in the early afternoon; thus yielding, compared to the Al-Fe roof, a 5^{o}C reduction at room temperature. However, comparing tile roof with three others as for their thermal behavior, it was found that tile roof transfers less energy to the room [9]. Al-Fe white coated shows relatively low temperatures compared to the former three roof materials. The room temperatures under white painted Al-Fe vary from 34^o C in the morning to a maximum of 40^{o}C in the afternoon, showing a better temperature comfort compared to Al-Fe and the tiles. Under the same atmospheric conditions, Al-Fe +3 or 6cm straw thick shows the lowest room temperatures. The room temperatures under such a roof material vary from approximately 30^{o}C in the morning to a maximum of 37^{o}C in the afternoon while the ambient temperature is at a maximum of 39^{o}C. Again, as expected, these types of modifications on Al-Fe are very beneficial for the thermal comfort in hot and dry zones of Sub-Sahara African regions. However, as the sun starts to set, Al-Fe + 3cm gives lower temperatures than even Al-Fe + 6cm.
Some important factors have also been looked at during the course of the present study. To improve the indoor comfort, it is recommended to plant trees at a giving distance from the openings of a building such as at the doors, windows, etc. We have compared the thermal behavior of Al-Fe /Al-Fe white painted roof material under the influence of the shade from a tree.

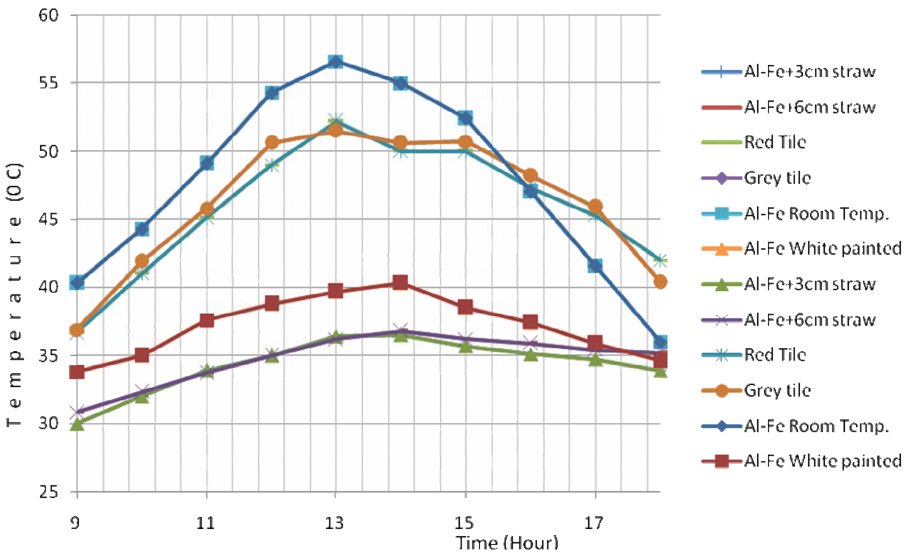

Figure 2. The temperatures of the rooms under various roof materials

The graphs of Figure 3 show that, up to 11:00 AM, the influence of the tree was not noticeable. However after 11:00 AM, a temperature gradient is observed with both the Al-Fe and Al-Fe white painted roof materials. The Al-Fe and the white painted Al-Fe show a temperature difference varying from 1 to 6o C due to the shading from a tree. This is the proof that tree plays key role in term of standing hot weather period. The presence of tree suitably located in a house lowers significantly the room temperatures. It has been demonstrated that protection of the buildings from the sun, primarily by shading, but also by the appropriate treatment of the building cover, that is, the use of reflective colors and surfaces, reduces the temperature of the room [10].
Another observation is the impact of water on the roof temperature. Four of the roof materials have been compared for the impact water has on their temperature behavior. All of them have been watered in the morning the way plants and flowers are in a house.
Al-Fe shows no change in temperature patterns, even though watered the same way as the others. Thus this roof material keeps its position of the most thermally unfavorable roof material. But it is worth to acknowledge that after watering the roof around 6:30AM, all of them have the same temperature trends

up to 9:00 AM when each one yields its appropriate curve. Here is a possible classification as far as thermal insulation:

- From 9:00AM to around 11:00 AM, grey tile roof offer the lowest temperature followed by the red tile, and lastly the Al-Fe white painted.
- From 11:00AM to 1:00 PM, the Al-Fe white painted becomes the second best roof material after the grey tile
- From 1:00PM to 5:00PM, Al-Fe white painted becomes the best roof material followed by the grey and red tile respectively.

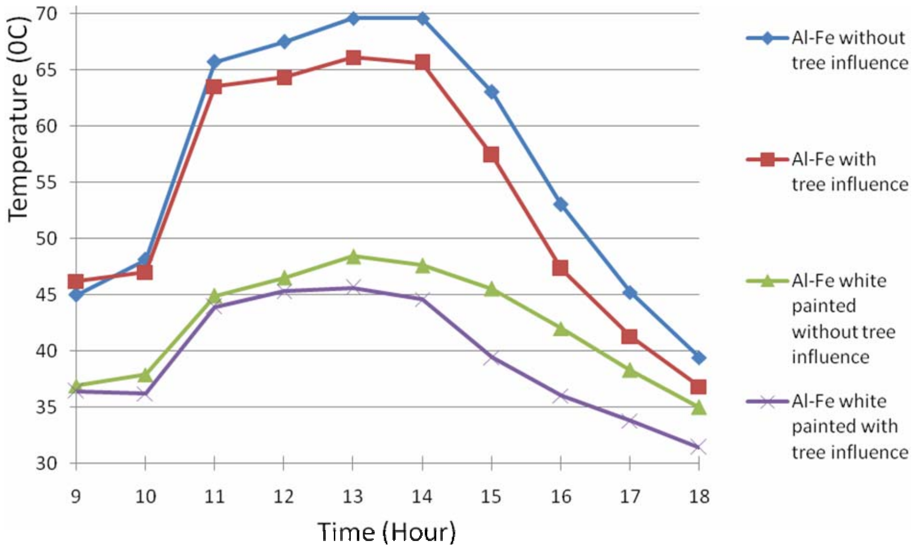

Figure 3. Al-Fe and Al-Fe white painted inner wall temperatures were measured with/out the influence of shading coming from a tree. A gain of 1 to 5°C was observed with the influence from the tree

The thermal behavior change observed so far is due to water retention capacity of grey and red tile versus the Al-Fe white painted which has none. In fact, the retained water will use the solar incoming energy to vaporize, thus lowering the temperature of such roofs. As it can be seen from the graphs of Figure 4, as soon as the retained water is vaporized, the roof materials recover their normal behavior. From this, it can be said that the vaporization of the retained water lasts from 9:00AM to 1:00PM with temperature gains with the grey tile of 28°C, 9°C, and 3°C respectively on Af-Fe, red tile, and Al-Fe white painted. A good application of this observation, basically in hot zones where grey tile is used is to water the roof twice a day (on sunny days), one by 6:30 AM and the second by 1:00PM. This will keep a gradient of about 20°C on average below the ambient temperature. The cost of using water to cool down the room must be compared to any other room air refreshment cost.

4. Conclusion

The present study has the merit of comparing various roof materials thermal behaviors under the same climatic conditions. While Al-Fe + x cm straw thick yields lower room temperatures, grey and red tile are good thermal material to consider in buildings, not only because of their thermal behavior, but also because of their aesthetic, their mechanical resistance and their water retention capacity. Painting white the Al-Fe largely improve the room temperature, giving the proof that under the tropics, slight modification on the most common used roof material may bring thermal comfort. However, grey tile, if adopted, with the watering possibility will turn out to be the best thermal roof in Sub-Saharan Africa regions.

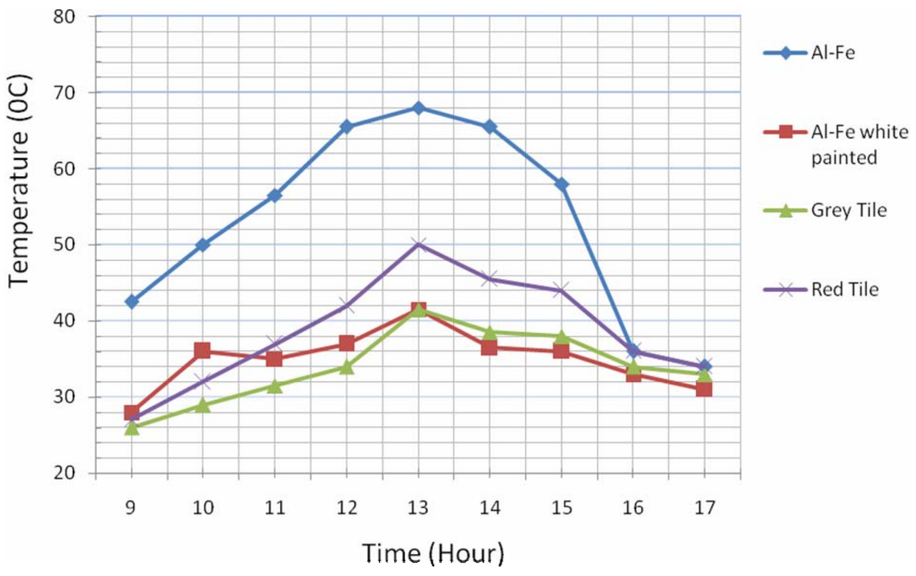

Figure 4. Effect of watering roof materials on roof inner wall temperature

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