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The effect of different wall materials at different orientations on indoor thermal comfort in residential buildings in kumasi, Ghana

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ABSTRACT

This paper explores the thermal properties of wall materials with different orientations to know which performs better within the warm-humid climatic Region of Kumasi. Four cases (sandcrete blocks, mud, bricks and concrete) were selected for the study with variations in each material. Thermal simulation analysis was employed as the means of comparison. The results illustrate a slightly better performance of the North and South orientations (29.8 to 30.0°C with relative humidity of 70.8 to 71%) than the East and West (29.9 to 30.1°C and 70.4 to 70.7%) in terms of indoor temperature and relative humidity. Mean radiant temperature recorded also followed a similar trend where the North and South orientations performed slightly better than the East and West. The West Orientation recorded surface outdoor solar gains of 92.6W/m^2 (the highest amongst the rest). Mean radiant temperature was comparatively high for the mud material during the early mornings to the late afternoons due to its high thermal conductivity. The study concludes that material differences do not significantly have any effect on indoor comfort but rather the orientation of the building. With the right materials and a stern conformity to passive design principles, buildings could be made comfortable for its occupants.

Keywords: Thermal performance, Comfort, Temperature, Relative humidity, Orientation.

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INTRODUCTION

Over the years, several definitions for thermal comfort have been given by various researchers. Hensen (1991) defined thermal comfort as a state in which there are no driving impulses to correct the environment by behaviour. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) defined thermal comfort as the condition of the mind in which satisfaction is expressed with the thermal environment (ANSI/ASHRAE, 2004). Givoni (1998), later provided one of the simplest definitions of thermal comfort and defined it operationally as the range of climatic conditions considered comfortable and acceptable to humans. This implied an absence of two basic sensations of discomfort: a thermal sensation of heat, and a sensation of skin wettedness (Givoni, 1998). Pino et al. (2012) also defined thermal comfort as the physical and psychological wellness of an individual when temperature, relative humidity, and air movement conditions are favourable for the activity that has to be developed.

From all the definitions, thermal comfort is achievable when temperature is under control. Szokolay (2004) underlines three variables that affect thermal comfort. These are environmental, personal and contributing factors. Thus, six parameters are necessary for thermal comfort assessment and calculations. These are: air temperatures, relative humidity, mean radiant temperature (which is equal to the air temperature), air velocity, metabolic rate and clothing insulation (Charles et al., 2005). In most thermal comfort studies, temperature have been indicated as the most important parameter since it is temperature that actually determines how occupants feel within spaces. Most authors have confirmed this assertion. Air temperature is often taken as the main design parameter for thermal comfort. Hence it is essential for occupants' well-being, productivity and efficiency (Adebamowo and Akande, 2010). Heidari and Sharples (2002) have suggested that air temperature alone is a good indicator. Thermal comfort field studies have also shown that occupants are susceptible to a wider range of indoor temperature most of which they feel comfortable by acclimatizing (Simons et al., 2014). The envelope of a building protects the interior space from the harsh exterior conditions. Consequently, the wall material of buildings does have an effect on the temperature within the interior space. For instance in a research on the thermal conductivity of building fabrics, (Soebarto, 2009) discovered that mud has a high thermal conductivity than sandcrete of the same size. In the olden days, typical Asante traditional houses were constructed with materials such as timber; bamboo and mud plaster with thatched roofs (Levy, 1999). With the passage of time, and within the warm humid climatic conditions, there was a gradual deterioration of the building fabric; (UNESCO, 2013). Currently, the use of sandcrete blocks, bricks and concrete with cement plaster and corrugated roofing sheets are mostly preferred in putting up traditional courtyard houses in Kumasi (Oppong and Badu, 2012). According to Guo (2010), a courtyard is an open space into the sky, square or rectangular in plan and surrounded by a group of buildings or principal rooms. Courtyards are very common traditional devices for day lighting, natural ventilation, heat gain control and social gatherings (Howlet et al., 2010). The study examines and compares the thermal performance of different mud, sandcrete, brick and concrete wall materials for courtyard houses through simulation analysis. The paper presents the results of the wall materials in terms of indoor temperature, relative humidity, mean radiant temperature, solar heat gain values, among others. The aim is to find out which wall material significantly reduces indoor thermal discomfort.

LITERATURE REVIEW

Thermal Mass

The thermal mass of a building material describes the ability of that material to absorb heat, store, and later release it either outdoor or indoor. Thermal mass can delay heat transfer through the envelope of a building, and help keep the interior cool during the day when the outside temperature is relatively higher (Amos- Abanyie, 2012). When thermal mass is exposed to the interior, it absorbs heat from internal sources and dampens the amplitude of the indoor temperature swing (Chenvidyakarn, 2007). This is particularly beneficial during warm periods, when the internal heat gains during the day is absorbed, and help to prevent an excessive temperature rise and reduction in the risk of overheating (Yam et al., 2003). A building with high thermal mass has the ability to absorb heat and provide a cooling effect which comes from the difference between the surface (radiant) temperature and that of the internal air. Szokolay (2004) accounts that absorptance/reflectance will strongly influence the solar heat input. Reardon (2010) agrees with Szokolay (2004) by asserting that porous materials with low specific heat exhibit low thermal mass effects. Additionally, good thermal conductivity and high reflectivity are also required for effective passive cooling by thermal mass.

Apart from high thermal mass, other strategies such as night ventilation and natural ventilation are known to reduce indoor temperature and the energy use in buildings around the world. For instance, Pfafferott et al. (2003) confirmed that night ventilation reduced the mean room temperature by 1.2 K during the daytime for a building in Freiburg/Germany and so did Geros et al. (1999) who also found the average reduction of the temperature in a building in Greece to be between 1.8 and 3 K after using night ventilation. Natural ventilation on the other hand can reach much higher ventilation rates than mechanical ventilation systems, which are especially designed for fresh air supply (Aggerholm, 2002). However, energy savings by natural ventilation can mostly only be evaluated when simulation tools are used as reported by Schulze and Eicker (2013). A range of studies using measurements and simulations in a collection of buildings showed air change rates between 5 and 22 per hour for cross ventilation and 1 and 4 for single-sided ventilation (Fisch and Zargari, 2009; Breesch,2006 and Eicker et al.,2006) was concluded to be effective in reducing the energy used in cooling the buildings. Schulze and Eicker (2013) in their studies reported that 'simulations showed that night ventilation is only suitable in buildings with sufficient and accessible thermal mass of about 75–100 kg/m^2 of floor space. The internal gains have to be limited to 30 W/m^2 of floor area'. In a tropical climate, Al - Tamimi et al. (2011) observed that the improvements in comfort by natural ventilation range between 9% and 41% (Kuala Lumpur in April). According to the authors, in a temperate climate, the improvements vary between 8% and 56%: a result which showed that natural ventilation has a good potential in a good potential in tropical and temperate climates according to Haase and Amato (2009).

Orientation

The orientation of a building is a contributing factor on how much energy it would use to provide thermal comfort for its occupants. Seok-Hyun et al. (2013) declare that the amount of sunshine that enters an interior space is affected by the orientation of a building. The designer of a window should consider the orientation of the window to be installed. On a normal summer day, the amount of sunshine at the east and west is small but the west requires a larger cooling load in the afternoon because of the afternoon sunshine. The south has a larger amount of sunshine but the solar radiation can be blocked easily by shading. Salmon (1999) establishes the fact that "buildings should be able to respond to changes in climate by the rejection of solar heat and have the thermal integrity to maintain internal comfort, despite the influence of climatic forces acting on the building envelope. In addition, the building should be able to retain cool conditions, in order to maintain comfort. In this regard, the exact solar orientation is not critical." Salmon however establishes that analyses of sun paths and wind directions have shown that elongated buildings should be oriented to the south. In addition, the best orientation for wind is the southwest whilst a compromise of 22.5° (south-southwest) should give the best orientation.

Contrary to Salmon's view, Lauber's (2005) recommendation was that the best orientation for buildings in the warm and humid countries should be +/- 30° from the prevailing wind direction. The author (Lauber) further states that the shell of air-conditioned buildings must be insulated, windproof and airtight. This suggests an orientation away from the prevailing wind direction, but there is no precise direction for air-conditioned buildings from Lauber (2005).

Szokolay (2004) also had a different proposal from the above mentioned authors. Szokolay suggested that in order to ensure maximum cross ventilation in a building, the major openings should face within 45° of the prevailing winds. All the above suggestions from these authors are for naturally ventilated buildings.

Hawkes (1996) has two groupings for buildings; the exclusive and selective modes. The exclusive mode has an automatically artificial environment. The shape is compact and tries to minimise the influence of the external environment, therefore, orientation is not important. The environment of the selective mode is controlled by automatic and manual means with a mixture Orientation is an important factor in this mode. This implies that buildings in the exclusive mode are most spaces are important and could be a factor in the determination of the orientation as corroborated by the other authors of natural and artificial variables. The shape is dispersed and seeks to maximise the use of ambient energy.

Further, a study conducted by Lam et al. (2004) on the impact of solar radiation on the facades of buildings in the tropics revealed that North and South facades have the lowest sun intensities. This varied from 43.6 and 74W/m^2 respectively. The eastern and western facades recorded the highest intensities ranging between 86.1 and 89.6W/m^2. From the study above, optimised orientation of buildings in the Tropics should be away from the direction of solar radiation. Orientation is therefore tied in with aspect ratio which is the ratio of the longer dimension of an oblong plan to the shorter (Szokolay, 2004). Szokolay further explains that depending on the temperature and radiation conditions, North and South walls should be longer than the East and West with an aspect ratio of about 1.3 to 2.0 (ibid).

RESEARCH METHODOLOGY

Parametric simulation was selected as a means of comparing the thermal performance of the wall materials. Four wall materials with different properties (Table 1) were selected for the studies. The selected materials are a representative of traditional buildings and the current trend of courtyard house wall materials. Figure 1 illustrates the schematic plan and the Tas model of the building. The internal conditions for the various spaces are also shown in Table 1.

Objective Data

Parametric simulation with the Thermal Analysis Software (Tas) was used as a means of comparing the thermal performance of the building design options. Tas is a suite of software products, which simulate the dynamic thermal performance of buildings and their systems (ESDL, 2014). It has a 3D graphics-based geometry input that includes a CAD link. Tas Systems is a HVAC systems/controls simulator, which may be directly coupled with the building simulator. It performs automatic airflow and plant sizing and total energy demand. Tas combines dynamic thermal simulation of the building structure with natural ventilation calculations, which likely to orient spaces anyhow and could have higher ndoor temperature values and energy performance levels. Those in the selective mode would orientate spaces to the direction of prevailing winds; functions of include advanced control functions on aperture opening and the ability to simulate complex mixed mode systems (ESDL, 2014). A weather file for Kumasi was generated via Meteotest (2008) and used for the thermal analysis. The adaptive model based on the work of Auliciems (1981) and recommended by Szokolay (2004) for 90% acceptability was used to derive the comfort zone for Kumasi after Koranteng (2010) (Table 2 and Figure. 2).

In Figure 2, a shift of the comfort zone to the lower (left) and to the higher (right) temperatures is demonstrated with the mean hourly temperature and relative humidity values in Kumasi for representative days in the months of

Table 1: General overview of selected materials

	Sandcrete Wall			Mud Wall			Brick Wall			Concrete Wall		
Properties	S1	S2	S3	M1	M2	M3	B1	B2	B3	C1	C2	C3
Width (m)	0.2	0.2	0.2	0.4	0.4	0.4	0.2	0.2	0.2	0.2	0.2	0.2
Conductance (W/m².K)	0.5	1.2	3.7	1.5	2.7	3.8	0.9	2.9	4.8	1.2	1.7	2.9
Density (kg/m³)	400	720	400	2050	2000	2400	720	1750	2000	950	1250	1520
U-Value (W/m².K)	0.47	1.0	2.4	1.2	2.0	2.5	0.8	2.0	2.9	1.0	1.4	2.1
Lighting Gains	$1W/m^2$											
Occupancy sensible Gains	$6\text{-}31W/m^2$											
Equipment sensible Gains	$16\text{-}94W/m^2$											
Ventilation	15ach											

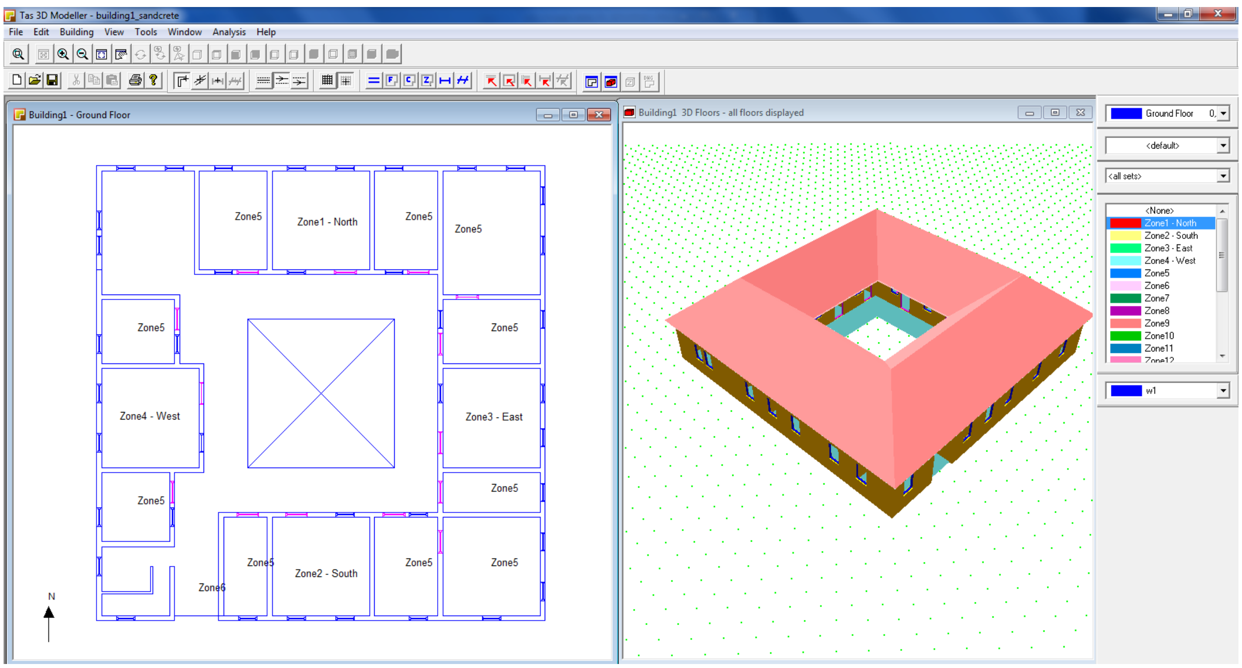

Figure 1: A model of a typical building in Tas

February and August. The shift of the comfort zone is minimal because of the minor difference in the outdoor temperature (Tn difference of 1.1°C, Table 2) during the warmest month (February) and the coolest month (August).

During the warmest period (dry season), mean temperature levels are high, and in some cases exceeding 30°C. However, the mean temperature levels humidity values are rather high, averagely 80% and where temperature and relative humidity values are high with hardly exceed 28°C during the rainy season, especially in the months of June, July and August. The effect is the experience of uncomfortable sensations. This is a characteristic of warm and humid countries, where temperature and relative humidity values are high with intense solar radiation and cloudy conditions existing most of the time.

Statistical Analysis of Data

In the Tas simulation programme, a courtyard building plan was imported from the AutoCAD application and a model was generated with the various wall materials (Table 1) for the various orientations (Figure 1). The weather file from Meteotest was used to run the simulation and the output data was exported to MS Excel application to calculate mean and annual values for comparison.

RESULTS AND DISCUSSION

The simulation results are presented. The results show how different wall materials orientated differently respond to solar radiation.

Table 2: Neutral temperature for 90% acceptability (Adaptive model)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
To.av.	26.5	28.6	28.4	27.9	27.6	26.6	25.5	25.3	26.0	26.4	27.0	27.3
Tn+2.5	28.3	29.0	28.9	28.8	28.7	28.3	28.0	27.9	28.2	28.3	28.5	28.6
Tn	25.8	26.5	26.4	26.3	26.2	25.8	25.5	25.4	25.7	25.8	26.0	26.1
Tn-2.5	23.3	24.0	23.9	23.8	23.7	23.3	23.0	22.9	23.2	23.3	23.5	23.6

Where $T_{O.av}$ is the mean temperature of the month Tn is neutrality temperature.

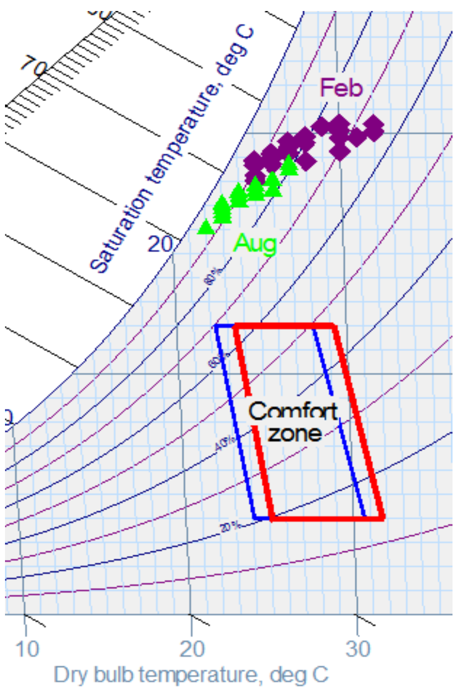

Figure 2: Mean hourly temperature and relative humidity values in Kumasi for representative days in the months of February and August

With a mean annual outdoor temperature value of 26.8°C and a relative humidity value of 84%, Table 3 shows the mean annual indoor temperature and relative humidity values for the various materials per orientation. Figure 3 illustrates the outdoor wind speed and direction for a reference day in both the warmest (February) and the coolest (August) months. Table 5 indicates the mean surface outdoor solar gain for the various constructions per orientation for a reference day in the warmest and coolest months which recorded same values for all the materials and the coolest months for the various constructions (Sandcrete (S), Mud (M), Brick (B) and Concrete (C) was also simulated. The various values as per the various orientations are insignificantly different. Conversely, the Western facades of the various materials showed some considerable disparity. Figures 4 to 9 show the radiant temperature results of the west orientation for the different wall materials.

Mean indoor annual temperature values ranged from 29.8 to 30°C with relative humidity values between 70.1 to 71.1% (Table 3). From the Table, the western orientation is slightly higher in temperature and lower in relative humidity. This finding is corroborated by Sedki et al. (2013). The authors found the eastern and western apartments of residential buildings in Cairo to have high neutrality temperatures. Therefore north and south orientations are recommended for buildings in the Warm-humid climates. Additionally, proper shading and landscape (Abreu et al., 2012; Ossen et al., 2008) could help reduce the indoor temperatures of the west orientation. The Table again shows that the distinction of the various materials does not really have any effect on the temperature and relative humidity as the values were similar. Comparable finding was reported by Rosangela (2002).

From Table 4 and 5, the west has the highest mean surface outdoor and indoor solar gains. This corroborates the findings of Lam et al. (2004) when they recorded a solar radiation of 89.6W/m^2 on the western facade. Although in their study, the western and the eastern facades recorded the highest intensities, the current study has the west and the south recording the highest intensities (Table 4). This is by virtue of the location of Kumasi (Ghana) on the Globe.

Mean radiant temperature recorded within the western orientation was the highest among the rest of the orientations. During the warmest month (Table 2), mean radiant temperature values recorded ranged from 28.9 to 31.6°C for all the materials. All the mud variations recorded higher temperatures during the mornings to the late afternoons during the warmest month. However, between the hours of 6 and 7 pm to midnight, it recorded the lowest temperature values ranging from 31.5 to 29.7°C. This is as a result of the thermal mass of mud which is able to store and redistribute the heat stored (E.E.S., 2012). Mean radiant temperature values during the coolest month range from 25.5 to 27.6°C for all the materials. The effect of the high radiant temperature causes thermal discomfort for occupants in the building (Atmaca et al., 2007). This result indicates that orientation to the west is not favorable in the tropics as some a authors have reported (Seok-Hyun et al., 2013

Table 3: Mean indoor annual temperature and relative humidity values for the various orientations per construction

	North		South		East		West	
Constructions	Temp (°C)	RH (%)	Temp (°C)	RH (%)	Temp (°C)	RH (%)	Temp (°C)	RH (%)
S1	29.9	70.7	29.9	70.6	30.1	70.6	30.0	70.4
S2	29.9	70.7	30.0	70.8	29.9	70.6	30.1	70.5
S3	29.9	71.1	29.9	71.0	29.9	70.9	29.9	70.7
M1	29.9	70.7	29.9	70.8	29.9	70.7	30.0	70.5
M2	29.9	70.8	29.9	70.9	29.9	70.8	30.0	70.6
M3	29.9	70.9	29.9	71.0	29.9	70.8	29.9	70.7
B1	29.9	70.7	29.9	70.7	30.0	70.6	30.0	70.4
B2	29.9	70.9	29.9	70.9	29.9	70.8	30.0	70.6
B3	29.9	71.0	29.8	71.0	29.9	70.9	29.9	70.7
C1	29.9	70.7	29.9	70.8	29.9	70.6	30.0	70.5
C2	29.9	70.8	29.9	70.8	29.9	70.7	30.0	70.5
C3	29.9	70.9	29.9	70.9	29.9	70.8	29.9	70.6

Table 4: Mean surface outdoor solar gains for the various constructions per orientation for a reference day in the warmest and coolest months.

	North (W/m²)	South (W/m²)	East (W/m²)	West (W/m²)	Diffused (W/m²)	Global Solar gains (W/m²)	Mean of Diffused and Global Solar gains (W/m²)
Warmest Month (Feb.)	60.6	79.4	72.2	92.6	347.6	253.5	300.5
Coolest month (Aug.)	28.8	28.7	28.8	28.8	135.3	134.2	134.8

Table 5: Mean surface indoor solar gains for the various constructions per orientation for a reference day in the warmest and coolest months.

	North (W/m²)	South (W/m²)	East (W/m²)	West (W/m²)
Warmest month (Feb.)	1.2	0.5	0.7	1.8
Coolest month (Aug.)	0.5	0.2	0.3	0.5

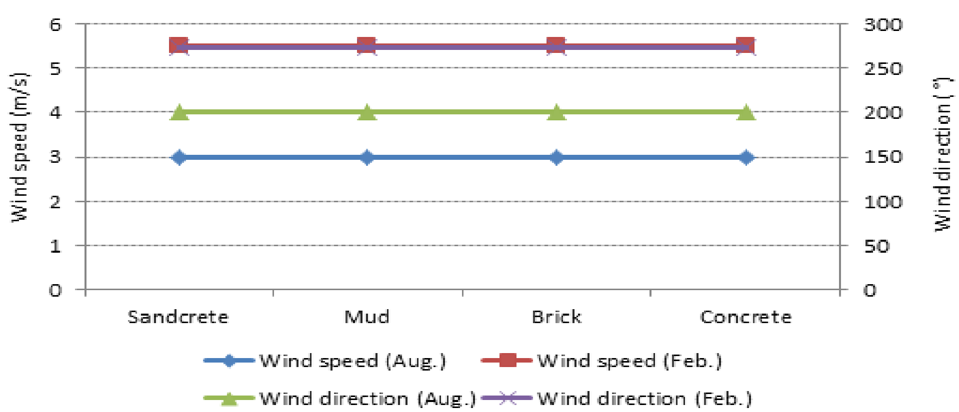

Figure 3: Mean Outdoor wind speed and direction for a reference day in the warmest and the coolest months.

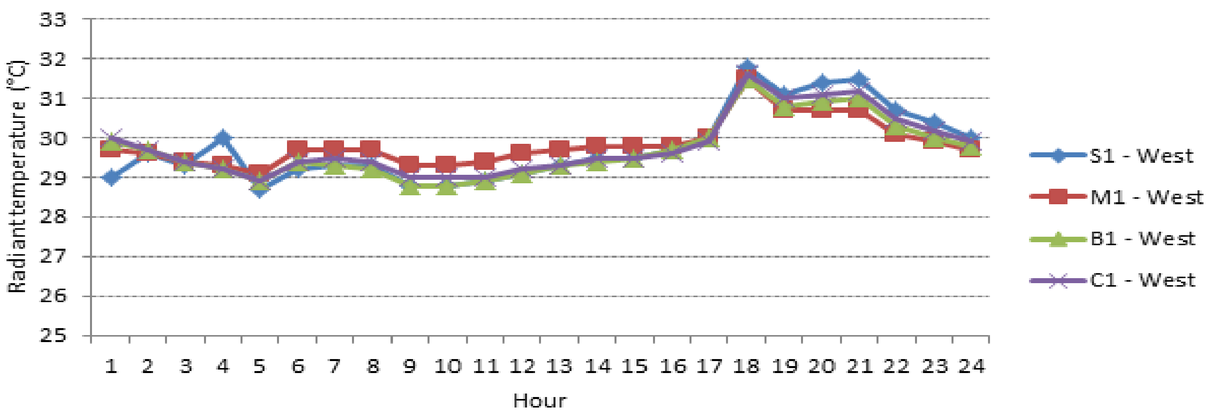

Figure 4: Radiant temperature (R.T.) for the west orientation of a typical reference day during the warmest month for the various construction types: Sandcrete (S1), Mud (M1), Brick (B1) and Concrete (C1).

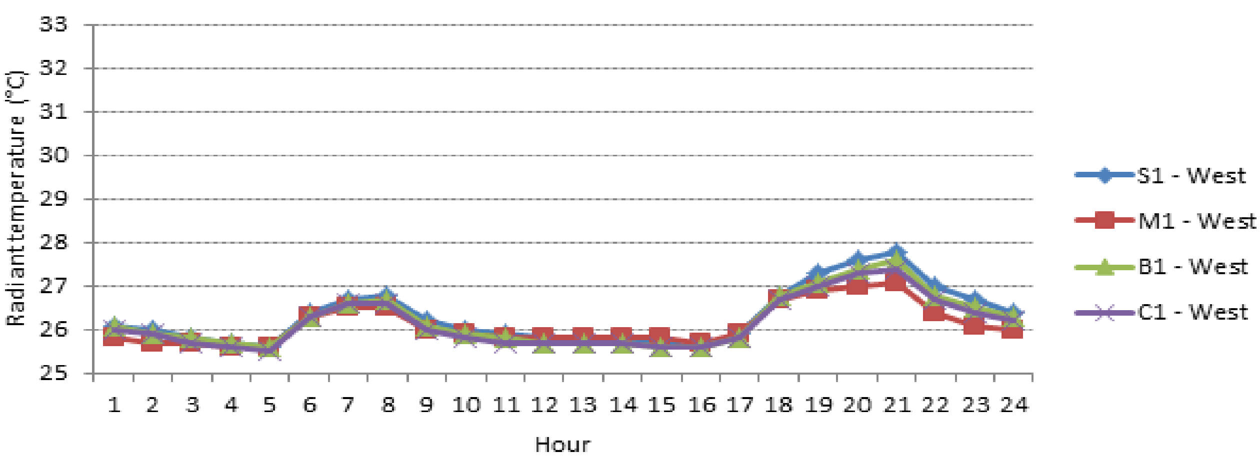

Figure 5: Radiant temperature (R.T.) for the west orientation of a typical reference day during the coolest month for the various construction types: Sandcrete (S1), Mud (M1), Brick (B1) and Concrete (C1)

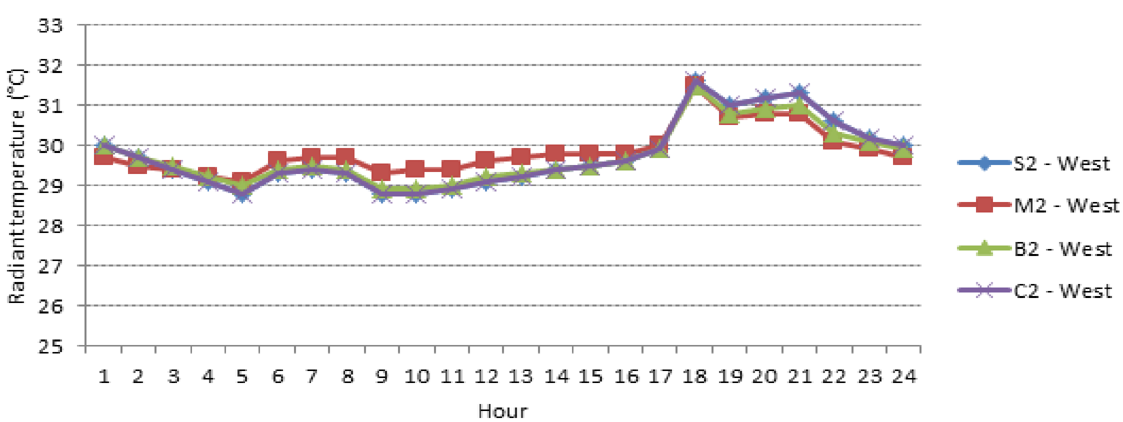

Figure 6: Radiant temperature (R.T.) for the west orientation of a typical reference day during the warmest month for the various construction types: Sandcrete (S2), Mud (M2), Brick (B2) and Concrete (C2)

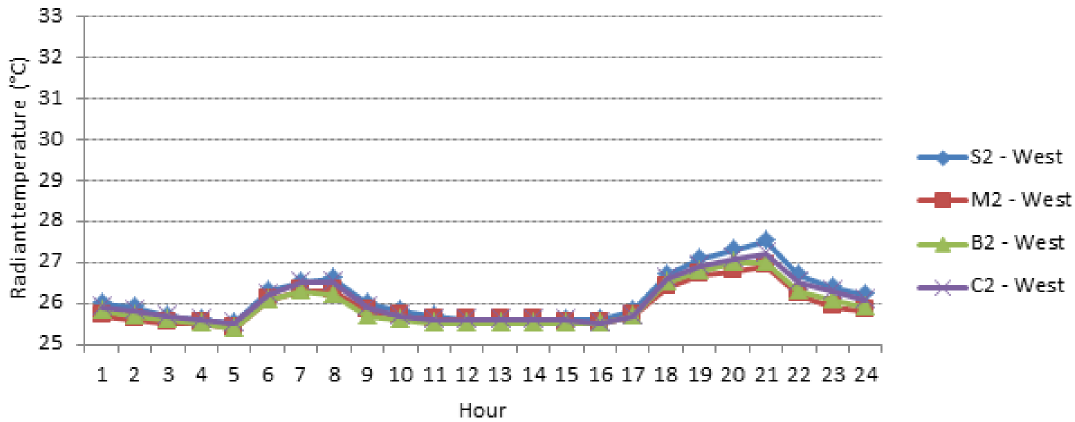

Figure 7: Radiant temperature (R.T.) for the west orientation of a typical reference day during the coolest month for the various construction types: Sandcrete (S2), Mud (M2), Brick (B2) and Concrete (C2).

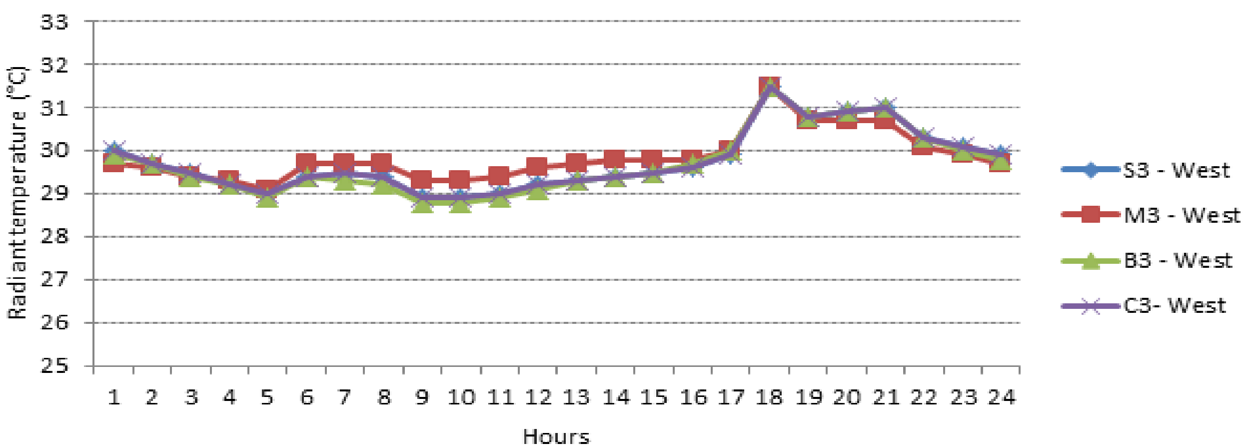

Figure 8: Radiant temperature (R.T.) for the west orientation of a typical reference day during the warmest month for the various construction types: Sandcrete (S3), Mud (M3), Brick (B3) and Concrete (C3).

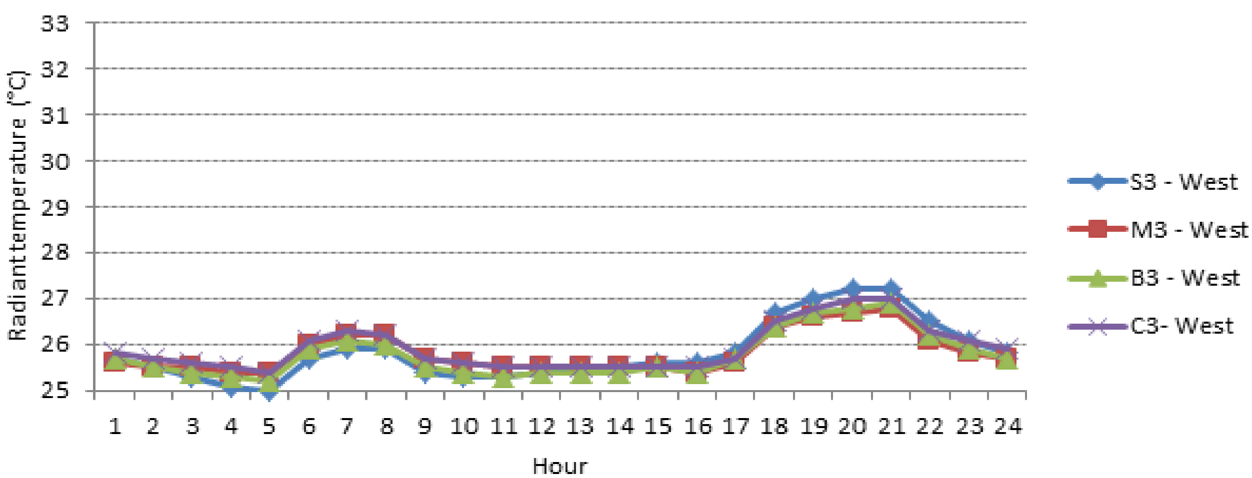

Figure 9: Radiant temperature (R.T.) for the west orientation of a typical reference day during the coolest month for the various construction types: Sandcrete (S3), Mud (M3), Brick (B3) and Concrete (C3).

Lauber, 2005; Szokolay, 2004; Salmon, 1999). During the coolest month, brick and mud seems to perform better than the other materials by temperature values ranging from 25.2 to 27°C.

CONCLUSION AND RECOMMENDATION

The effect of different wall materials at different orientations on indoor comfort has been studied. The air was to find out which wall material could significantly reduce indoor thermal discomfort. The study revealed that in terms of indoor annual temperature and relative humidity, the different materials recorded similar values: giving an indication that different wall materials do not significantly alter the conditions within a space. However, in terms of orientation, the West had values that were relatively higher than the other orientations by 0.1°C.Similar trend was found with the surface solar gains (where the difference between the west and the next highest values was 13.2W/m^2) and the mean radiant temperatures (0.1 to 0.3°C) where the West was recorded to have slightly higher values than the East, South and the North. In effect, it can be concluded that the West orientation produces thermal discomfort due to the intense solar radiation from the sun. Again from the study, the wall densities, u-values and conductance all did not seem to have any effect on the outcome of the results. In orienting a building in the warm humid climate, large wall surfaces should be positioned away from the west as possible. Additionally, the use of landscape elements (pergolas, marquises) and the disposition of trees, together with the use of low absorbing or reflective surface materials, can minimize the problems provoked by excessive solar radiation.

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