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Assessing Residential Building Energy Efficiency in the Caribbean Environment: A Case Study of Trinidad and Tobago

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Abstract: *The energy performance of building is closely linked to the energy performance of the building envelope. Buildings in the Caribbean countries are experiencing high heat, humidity, rainfall, and extreme weather events. Compared with "Temperate Regions", humid tropical climates can affect buildings through higher rates of deterioration and uncomfortable conditions for the occupants. The transfer of building technology and policies developed in temperate regions that are sometimes irrelevant and often inappropriate for hot and humid regions, therefore there is acute need to initiate rigorous models in order to develop typical sustainable buildings for warm humid regions such as in the Caribbean countries. As such, the current research was undertaking to investigate and recommend effective passive strategy for achieving sustainable building energy efficiency in warm humid regions. In order to achieve this aim, an investigation was conducted on the impact of building envelope systems such as roof and wall design solutions on the building energy efficiency through experimental approach using three building physical models attached with air-conditioning system each. Subsequently, the performance of the building envelope physical models in terms of energy consumption, cooling load, indoor temperature, indoor relative and humidity was monitored through Lascar EasyLog USB-2-LCD data logger sensors and Multifunctional Mini Ammeter. The findings derived from this study have proved that, the short term strategies could be applied for achieving sustainable building energy efficiency for humid warm climatic zones. Specifically, it was found that, the insulated galvanised and standing seam roofing systems are more energy efficient and cost effective, while in the longer terms, flat slab concrete roofing system is more energy efficient and cost effective.*

Keywords: *Energy Performance; Building Envelope; Cooling Load*

1. Introduction

According to State of the tropics report (2017) published by the James Cook University, it reported that the buildings in the "Tropics" are usually exposed to environmental conditions, including high heat, humidity, rainfall, and extreme weather events, not experienced elsewhere. Compared with temperate regions, tropical climates can affect infrastructure through higher rates of deterioration. The transfer of infrastructure, technology and policies developed in other parts of the world are therefore often inappropriate for tropical conditions, pointing to the need for increasing opportunities, capacity and investment for developing and scaling up local infrastructure design and innovations.

In India, the Energy demand had traditionally been dominated by the buildings (India Energy Output, 2015). In the buildings sector, a key driver of consumption in both rural and urban areas has been rising levels of appliance ownership, especially of fans and televisions, and an increase in refrigerators and air conditioners over the latter part of the 2000s. As a result, electricity demand in the buildings sector grew at an average rate of 8% per year over 10 years. The interaction between building envelope and the external environment is an important issue in developing sustainable tropical residential structures. Considering the urgency of saving the world's energy reserve, energy-conscious buildings are becoming an important part of design helping to minimise demands on non-renewable resources while providing better natural ventilation than was previously possible (Brown and Herendeen, 1996). As such, it is important to understand the energy saving potential of the building envelope in energy conscious building design (Mwasha, et. al. 2011; Iwaro and Mwasha 2013).

The energy performance of building envelope has direct influence on the level of energy consumption of building. It is therefore necessary to consider building envelope as effective sustainable passive strategy for achieving sustainable building energy efficiency especially in hot humid regions of the world (Iwaro 2016). As such, this paper investigated the impact of sustainable envelope design in warm humid region such as Trinidad and Tobago and other Caribbean countries.

2. Literature Review

2.1 Energy Efficiency Strategies

According to Hoffman, and Pienaar (2013) the awareness of energy inefficiency and global climate change has significantly impacted the construction sector in recent years. In warm and humid regions such as Caribbean countries, the building envelopes are the largest component of building which consumes large amount of energy at each stage of its development from design, construction through to operation and final demolition. In Trinidad and Tobago, the residential sector consumes 29% of total electricity (Natacha et. al. (2015). The average household consumption is the highest in the CARICOM region, and it is considered that there is a large potential for energy savings through efficiency in the sector. The energy consumption at each stage in the building envelope development is largely influenced by how the envelope was constructed, building orientation, outside temperature, window areas, light systems, air conditioning and ventilation, level of insulation and the thermal characteristics of building envelope i.e. walls and roofs (Cole and Rousseau (1992); Spence and Mulligan (1995), Hui (2001); Ding (2004); Jamie (2007)).

In warm humid regions, the cooling energy needed by building can be significantly reduced with the use of cool materials as suggested by Santamouris, Synnefa and Karlessi (2011) and Vincenzo, Gianpiero and Luigi (2013) as well as proper insulation of building envelope through wall and roof components as suggested by Irene and Robert (2007). Moreover, improving the energy efficiency of the building envelope glazing system will bring about reduction in energy consumption and improvement in building energy efficiency (Stansfield 2001). Building envelope can also impact overall building energy consumption through its shading devices (Irene and Robert 2007). In the study conducted by Cheun et al. (2005) using the passive thermal building envelope design strategies such as insulation, colour, glazing system and shading devices, they found that, on using passive energy efficient strategies, the annual required cooling energy was reduced from 3056 KWh to 2252 KWh. The passive energy efficient strategies include adding extruded polystyrene (XPS) thermal insulation in walls, white washing external walls, reflective coated glass window glazing, 1.5m over hangs and wing wall to all windows (Cheung et al. 2005).

According to Sharma (2013) energy savings of 31.4% and peak load saving of 36.8% were recorded for high rise buildings by implementing passive energy efficient strategies. In another study, the energy effective building envelope design was found to have saved as much as 35% and 47% of the total energy and peak cooling demands respectively (Chan and Cow 1998). In Greece, the thermal insulation in walls, roof, floor, and low infiltration strategies were found to reduce energy consumption by 20-40% and 20% respectively. According to the same study, light colored roof and external walls reduced the spaced cooling load by 30% and 2-4% respectively (Balaras et al. 2000). However, the effectiveness of building envelope on energy consumption in hot humid regions is still not well elaborated in the literature reviewed. In order to understand the effectiveness of building envelope on energy consumption in warm humid zones, a small scaled building envelope physical model was used to simulate building performance in a natural environment in order to actually justify the benefits of the proposed envelope design options in hot climatic regions. Hence, the current research was undertaking to investigate and recommend effective sustainable passive strategies for achieving sustainable building energy efficiency in hot climatic regions.

2.2 Building Envelope as Environmental Load Regulator in Warm Humid Regions

According to Irene and Robert (2007), building envelope has been described as the first line of defence against the undesirable external impacts on building such as Carbon emission, pollution, climate change, and also provides indoor conditions suitable for human comfort (Lucuik 2005). Building envelope serves as a thermal barrier and plays an important role in regulating interior temperatures and determines the amount of energy needed to maintain thermal comfort (Centre for Climate Change and Energy Solution 2015). In addition, building envelope was defined as a dynamic system that responds to the variability in surrounding environments such as external radiation, climate conditions and internal requirements for occupant's comfort (Mary 2010). As shown in Figure 1 the environmental loads on building envelope include the loads generated within the natural and built environment, industrial and urban environment, geo environment and indoor environment (Aksamija 2009) and Aksamija (2013). Besides, the impact of environment on building envelope and the impact of building envelope on the environment necessitated the need to make building envelope sustainable (Iwaro and Mwasha 2013). However, making building envelope systems sustainable to undertake these regulatory and protection tasks for tropical residential structures in most developing countries has been the major challenge.

Figure 1 illustrates the regulatory and protective functions of the building envelope in building against these environmental loads. As suggested by Hegger et al. (2008); DFW (2011a) and (DFW 2011b) building envelope interacts with: exterior environment, interior environment. Also the building envelope system interacts with the physical system of building in the process of separating the interior environment from the exterior environment, comfort and building sustainability. Therefore, the sustainable performance of building depends on the geometrical dimensions of the building envelope components. As such, the building envelope and its components are the major determinants of the amount of heat gain or loss in a building (ECBC 2013a). It means that in order for the residential building

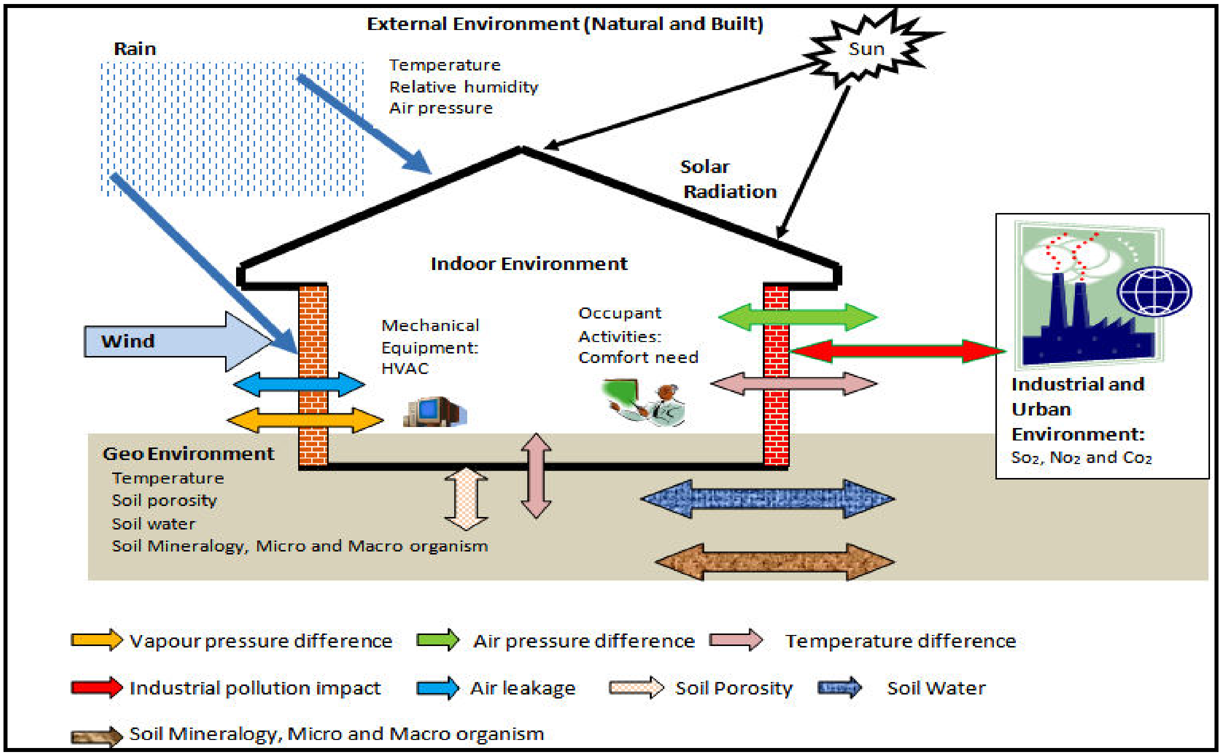

Figure 1. Environmental loads on building envelope

structures in warm tropical climatic region to be sustainable in view of the numerous environmental loads, it is necessary that the building envelope systems be made sustainable.

2.3 Heat Exchange and the Mechanism of Control in Building Envelope in Warm and Humid Regions

Solar radiation is the main source of heat loading in the tropics and one of the main functions of building envelope is to prevent the solar radiation from reaching the indoor environment. According to Szokolay et al. (2010), the conduction of heat may occur through the walls either inwards or outwards, the rate at which it occurs was denoted as Q_c (convective and radiant components in the transfer of the same heat at the surfaces are included in the term 'transmittance). Also, the effects of solar radiation on opaque surfaces can be included in the above by using the solar-air temperature concept, but through the transparent surfaces, the solar heat gain through the windows must be considered separately denoted as: Q_s.

While, the heat exchange in either direction may take place with the movement of air, i.e. ventilation denoted as Q_v. An internal heat gain may result from the heat output of human bodies, pets, lamps, motors and appliances is denoted as Q_i. The flow rate of such mechanical controls is denoted as Q_m and if the evaporation is taking place on the surface of the building envelope and the vapours are removed, this will trigger a cooling effect denoted as Q_e. The cooling and heating of the building envelope can be expressed in equation 1

$$Q_i + Q_s \pm Q_c \pm Q_v \pm Q_m - Q_e = 0 \quad (1)$$

This cooling effect brings about the cool temperature being experienced inside the building by the occupants. Moreover, in view of the importance of removing heat from the indoor environment, there may be need to introduce other passive solar control measures to reduce and control the solar radiation load on the walls, windows and roof of the building envelope using solar heat control mechanism.

2.4 Solar Control of Heat Gain in Warm and Humid Regions

Glass windows are one of the greatest sources of heat gain into the building. In this case, the magnitude of solar-air temperature is influenced by factors such as absorbance and surface conductance. Since the window glasses are practically transparent for short-wave infrared radiation emitted by the sun. However, almost opaque for long wave radiation is emitted by irradiated objects in the room. The consequence of this is that the radiant heat, once it has entered through a window, is trapped inside the building causing solar overheating snags. As such, there are four methods recommended for the reduction of solar heat gain through windows. These are: Orientation and window size, internal blinds and curtains, special glasses and external shading devices.

Using these strategies, the transmittance (t) through the window glasses may be reduced from t = 74% to less than t = 42%. However, one difficulty is that the reduction in transmittance is accompanied by a corresponding increase in absorbance. Absorbed heat will be re-radiated and converted partly to the outside and partly to the inside. Hence, the net improvement will not be as great as the reduction in transmittance.

2.5 Thermal Insulation

According to Balaras et al. (2000), in Greece, thermal insulation in walls, roof and floor reduced energy consumption by 20-40%. Also, external shading and light coloured roof and external walls were found to reduce the space cooling load by 30% and 24% respectively. This means that building envelope with a low U-value will reduce all forms of conducting heat transfer through the building envelope. Thermal insulation of building envelope plays an important role in meeting the demands of improving the energy efficiency of residential building (Sharma 2013). This requires using insulation materials with low thermal conductivity and overall thermal heat transfer resistance, U-value in buildings. However, in the case where there is a big heat gain into the building with a strong solar radiation, it is the solar-air temperature value that will be evaluated to find the temperature difference. In case, the temperature difference is small, the actual motion force for heat flow may be large thereby suggesting the importance of insulation in buildings.

2.6 Thermal Capacity and Thermal Mass Effect

Some studies have referred to the effect of thermal capacity as capacitive insulation provided by low conductivity materials and low transmittance construction (Szokolay et al. 2010). For instance, the variation of climatic conditions produces a non-steady state, consequently, diurnal variations produce an approximately repetitive 24-hour cycle of increasing and decreasing temperatures. As such, the effect of this variation in buildings is that, in the hot period heat flows from the environment into the buildings, where some of it is stored and at night during the cool period, the heat flow is reversed from the building to the environment. Moreover, as the outdoor temperatures increase, the heat starts entering the outer surface of the wall. Subsequently, each particle in the wall absorbs a certain amount of heat for every degree rise in temperature, depending on the specific heat of the wall material.

The heat to the next particle will only be transmitted after the temperature of the first particle has increased. Consequently, the corresponding increase of the internal surface temperature will be delayed as shown by the broken line in Figure 2. As such, the outdoor temperature will have resulted in its peak and started decreasing before the inner surface temperature reached some level. From this point, the heat stored in the wall will be dissipated partly to the outside and only partly to the inside. This slowing of the flow of heat is called "thermal lag" (or time lag), and is measured as the time difference between peak temperature on the outside surface of a building element and the peak temperature on the inside surface. Some materials, like glass, do not have much of a thermal lag. But the thermal lag can be as long as eight or nine hours for constructions with high thermal mass like double-brick or rammed earth walls.

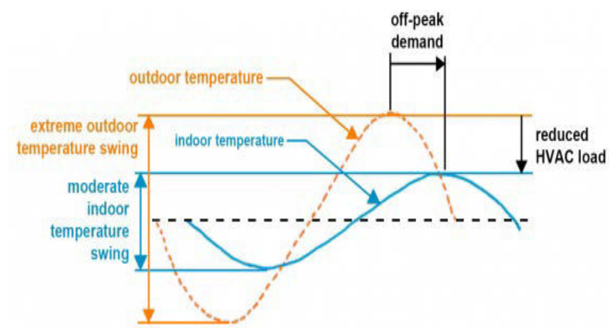

Figure 2. Lag-time and moderation of temperatures due to thermal mass
Source: Based on Autodesk (2016)

It may be several hours, however, before this temperature "spike" is seen at the inside surface of the wall. The reason is that some heat is being stored in the wall material. This heat is stored in the wall material until it has absorbed as much as it can (saturated). Heat will then flow to the inside, based on the conductivity of the material. As the outdoor temperature cools, an increasing proportion of this stored heat flows outwards.

The lag-time shown in Figure 1 does not represent the behavior of building envelope in hot humid climate regions since in these regions there are minimum variation of high and low temperatures. The air temperature during the day is between 27^{o}C and 32^{o}C. The relative humidity remains high, at about 75% for most of the time, but it may vary from 55% to almost 100%. The vapour pressure is also steady in the region with 2,500 to 3,000 N/m^2. In this paper the models are created to investigate the effects of varying building envelope components on fluctuation of the external and internal environment.

3. Modelling of Building Envelope Systems' Performance in Warm and Humid Climate

3.1 External Environment in Warm and Humid Climate Regions

The interaction of solar radiation with the atmospheric gravitational forces together with the distribution of land and sea masses, gives rise to the infinite variety of climates. According to Szokolay et al. (2004), the tropical regions of earth comprise of warm-humid equatorial climate, hot-dry desert climate and monsoon climate. The same authors pointed out that the warm humid equatorial climates are found in a belt near the equator which extends to about 15^{o}C N and S. Surprisingly most of the developing countries such as Africa, Asia, Pacific and the Caribbean Islands are found within this region.

In this warm humid climatic region, there are little seasonally variations throughout the year. The air temperature during the day is between 27^{o}C and 32^{o}C. The relative humidity remains high, at about 75% for most of the time, but it may vary from 55% to almost 100%. The vapour pressure is also steady in the region with 2,500 to 3,000 N/m^{2}. Furthermore, the solar radiation is partly reflected and partly scattered by the cloud cover on the high vapour content of the atmosphere, hence, the radiation reaching the ground is diffused and strong. Typically for these regions, the wind velocities are typically low, with frequent calm periods.

On the other hand, the islands within the equatorial belt and in the trade wind zones belong to warm humid island climate type. The countries within this region include the Caribbean, Trinidad, Philippines and other islands in the Indian and Pacific Ocean. The air temperature i.e. (Dry bulb Temperature) DBT ranges between 29 ^{o}C and 32^{o}C, while night time is normally between 18 ^{o}C - 24 ^{o}C. The relative humidity varies between 55% and 100%, while the vapour pressure varies between 1,705 and 2,500 N/m^{2}. The solar radiation is strong and mainly direct, with a very small diffuse component. The predominant trade wind blows at a steady 6-7 m/m and provides relief from heat and humidity. However, the much higher velocities occur during hurricane seasons. Different from most of the Caribbean Islands, the Trinidad's geographical location put it on the Southern periphery of the North Atlantic hurricane basin.

3.1.1 The Local Climate in Trinidad and Tobago

According to the Trinidad Meteorological Office Information (Metrological Office 2017), Trinidad and Tobago's close proximity to the equator enables the country to have two climate types producing two opposing seasons differentiated by characteristic dry and wet seasons. The dry season which occurs during January to May symbolises a tropical maritime climate that is characterised by moderate to strong low level winds, warm days and cool nights, with rainfall mostly in the form of showers. Also, a moist equatorial climate that is characterised by low wind speeds, hot humid days and nights, an increased rainfall which results mostly from migratory and latitudinal shifts at equatorial weather systems. This climate symbolises the wet season during June to December. During the wet season is the hurricane seasons which runs from June to November, peaking between August and October. Trinidad's geographical location puts it on the Southern periphery of the North Atlantic hurricane basin. As such, Trinidad is not directly affected by storms as frequent as Tobago. However, peripheral weather associated with tropical storm systems normally impact Trinidad and Tobago. Their annual maximum and minimum temperatures are 31.3^{o}C and 22.7^{o}C, respectively with a mean daily temperature of 26.5^{o}C. These external environmental data will be used to assess the energy efficiency of the building envelope models.

3.2 Model Description

This experimental method used in this study has been extensively used in other studies, such as Cabeza et al. (2010) in an experimental study showing the performance of insulation materials in construction, where they used the concrete columns with reinforced steel bars as envelope frame structure. Similarly, In Dimdina et al. (2013)'s study on measuring the influence of building envelope materials on energy efficiency and indoor environment, five identical small envelope models with external walls of different composite building materials were used. Also, studies from Sakipova et al. (2013) on energy efficiency and sustainability of low energy houses in Latvian climate conditions used five identical small envelope models. Likewise studies by Borodinecs and Zemits (2012) and Ozolinsh and Jakorich (2012) successfully used small envelope models. In all these studies, the results from their physical envelope models studies were extrapolated to the full scale residential building.

3.2.1 Building Envelope Systems Insulated with Fibre Glass

The study investigated the impact of building envelope systems such as roof and wall design solutions on the building energy efficiency through experimental approach using three (3) building physical models attached with air-conditioning system each.

The three (3) identical small-scale test models (1.524 m long x 1.219 m wide x 1.524 m high) as shown in Figure 3 were built to determine the effect of the different envelope design solutions in the building energy efficiency performance. The difference between the models is the type of masonry wall and roof materials used. In the process, eleven (11) different model designs were used. The testing was done in two phases: Phase 1- building envelope insulation, and Phase 2 - roof system insulation.

In the Phase 1, three model design solutions were tested. The models include: Models A, B and C as shown in Figure 3, they were constructed with 100 mm concrete block, 150 mm concrete block, 100 mm clay, clay tile roofing system, corrugated standing steam roofing system, galvanised iron roofing system, steel frame structure, wood roof frame structure, 100mm concrete slab, 12,000 BTU Panasonic air conditioning system and 1.5 inches Fibre glass insulation for wall and ceiling.

Figure 3. Physical building envelope models

The envelope design solutions, were compared with each other to determine their benefits and impacts to the building energy efficiency and impacts to the building energy efficiency.

3.2.2 Roof Systems with Fibre Glass Insulation

In the second phase, five (5) model designs were tested based on three identical models as shown in Figures 4, 5 and 6. The models were constructed with 150mm concrete block, 100 mm clay, corrugated standing steam roof, corrugated galvanised iron sheet roof, 100mm concrete roof, steel frame structure, wood roof frame structure, 100 mm concrete slab, 12,000 BTU Panasonic air conditioning system and ceiling insulated with 1.5 inches Fibre glass.

Figure 4. Model 1 - 100mm Clay block walls and corrugated galvanised iron sheeting roof

The models were tested with and without insulation, with and without air conditioning system to develop baseline conditions which would be used to determine the benefits of the roof materials, roof system and the insulator to building energy efficiency. Table 1 shows a summary of the insulations and materials used for the different masonry unit walls tested.

Figure 5. Model 2 – 150mm Concrete block walls and corrugated standing seam roof

Figure 6. Model 3 - 150mm Concrete block masonry walls and concrete roof

Table 1. Components and material used in the envelope physical models

Components	Model A	Model B	Model C
Roof Sheeting	Red clay tile	26G corrugated standing seam sheeting	26G galvanised aluminium sheeting
Roof Frame	2” X 4” Timber	2” X 4” Timber	2” X 4” Timber
Structural Frame	4” steel RHS	4” steel RHS	4” steel RHS
Ceiling	6mm plywood ceiling board and 1.5”fibre glass sheet	1.5” fibre glass sheet	1.5” fibre glass sheet
Floor Floor finishes	4” concrete slab Carpet	4” concrete slab Terrazzo	4” concrete slab Wood
Wall Wall insulation	100mm x 200mm x 400mm concrete block 1.5”fibre glass sheet	100mm x 200mm x300mm clay block 1.5”fibre glass sheet	150mm x 200mm x 400mm concrete block 1.5”fibre glass sheet

4. Experimental Methodology and Procedures

The models in each phase were tested at same times and subjected to same environmental conditions. Subsequently, the performance of the building envelope physical models in terms of energy consumption, cooling load, indoor and outdoor temperature was monitored through Lascar EasyLog USB-2-LCD data logger sensors and Multifunctional Mini Ammeter. This was aimed at monitoring the impact of outdoor temperature and humidity on the envelope energy consumption and indoor temperature. Also, these parameters were monitored in January, March and June with A/C and without AC. In the process of monitoring, each envelope model was tested for 2 days with air conditioning (A/C) for three months, while the mini ammeter measured the cumulative energy consumption in kWh at interval of 2 hrs. Air conditioning unit was incorporated into the experiment in order to investigate the impact of building envelope materials on the envelope energy efficiency performance. This was done by measuring the energy consumption associated with each envelope model tested.

Along with the Multifunctional Mini Ammeter reading, Lascar EasyLog USB Data Logger sensors were also installed on the outside roof, outside west wall and inside west wall of the models to monitor outdoor and indoor humidity and air temperature. The logger sensors were set to record humidity and air dry bulb temperature information at the time interval of 5 min for 2 days continuous reading with air conditioning cooling.

Moreover, the parameters related to type of external walls and their insulation that influenced the internal environment were identified as Relative Humidity and DBT. For each model, these parameters were tested every 5 minutes for 2 days over a period of 48 hours, both with and without Air Condition. The energy consumption was measured every 2 hours over the 48-hour period for two days in three months when the models were tested with Air Condition. This would enable correlations with the insulation and the energy consumption necessary to achieve energy efficiency.

The data collected for concrete and clay masonry unit walls were analysed and compared to determine which insulation performed the best for each wall. Likewise, the data collected from these roof systems were analysed and compared to determine which insulation performed the best for each roof. Each model was tested for two days with Air Condition and two days without Air Condition. The models were tested at same time period under same external environment conditions. The research parameters were monitored using the Lascar Easy Log USB-2-LCD Humidity, Temperature and Dew point USB data logger sensors.

The energy efficiency performance of each physical envelope model was measured using Multi-functional Mini Ammeter. The U values and area of the components used are shown in Tables 2, 3 and 4.

Table 2. Envelope design alternative A

Load components	Area(m^2)	U-value (m^2K/W)
Roof	98.8	1.208
Wall	99.1	3.021
Floor	77.8	0.860
Window	15.1	3.700
Door	3.9	2.612
Infiltration	-	-

Table 3. Envelope design alternative B

Load components	Area(m^2)	U-value (m^2K/W)
Roof	98.8	0.573
Wall	99.1	3.876
Floor	77.8	0.940
Window	15.1	2.700
Door	3.9	3.129
Infiltration	-	-

Table 4 Envelope design alternative C

Load components	Area(m^2)	U-value (m^2K/W)
Roof	98.8	0.571
Wall	99.1	3.071
Floor	77.8	0.840
Window	15.1	7.370
Door	3.9	4.117
Infiltration	-	-

5. Data Analysis and Results

5.1 Energy Efficiency Performance of Insulated Building Envelope

The average energy consumption data for the models were collected at two hours' interval over a 48 hours (2 days) period. The result shows in Figure 7 that the energy consumption of the models increases as the outside temperature increases and decreases as the levels of the sun exposure decrease. The result further shows that the energy consumption of the models was at the peak between the hours of 10.00 am to 4.00 pm. In these specified periods, the average energy consumption of Model "B" was the lowest with 0.3420 kWh while Model "C" has the average energy consumption with 0.4683 kwh. This indicates higher energy efficiency performance in Model "B" when compared with other two models.

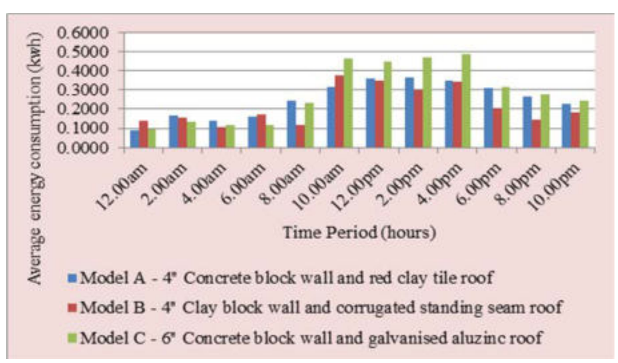

Figure 7. Average energy consumption at two-hour interval for 2 days (48hours)

It can be seen that more energy was consumed between the periods of 6.00 pm - 10.00 pm than the periods of 12.00 am - 8.00 am. This is because the building envelope stores heat energy during the period of 6.00 pm - 10.00 pm, and releases the heat energy during the periods of 12.00 am - 8.00am for cooling and temperature stabilisation. Moreover, the energy consumed between the periods of 12.00 am - 8.00 am was lower due to the absence of solar radiation from sun and low heat gain into the envelope indoor environment. The result further revealed that energy consumption was the greatest in Model ‘C” during the day with the highest thermal mass of 150 mm (6”) concrete block wall, while Model “A” has the highest energy consumption during the night due the presence of thermal mass in the100mm (4”) concrete block wall and red clay tile roof. This means that more energy is stored at night in model “A” than the other two models.

Moreover, given the set indoor temperature at 24 ^{o}C, model B recorded the lowest indoor temperature when compared with other two models indoor temperature profile performance. The Figure 8 shows that, within the peak period between 10.00 am – 4.00 pm, the indoor temperature of model B was the least among the three models tested with about 2^{o}C above the 24 ^{o}C set indoor temperature at its peak temperature. Besides, model B consumed the least amount of energy to cool the outdoor temperature to the indoor temperature of 26 ^{o}C at its peak temperature when compared to the other two models. This suggests better energy efficiency performance of model B. This is because the model was able to reduce the impact of outdoor temperature. In addition, model B continues to maintain the least temperature even after the outdoor temperature and sun radiation started to decline between 8.00 pm – 12.00 am.

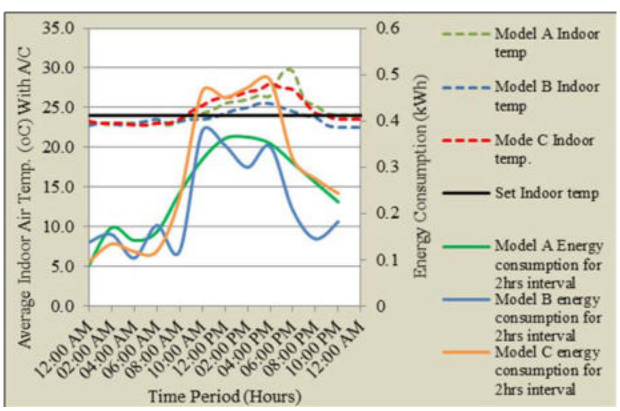

Figure 8. Energy consumption and indoor air temperature

5.1.1 Energy Consumption and Relative Humidity Performance of the Models

Indoor relative humidity represents the percentage of the available energy that has been used for cooling. In model C, the indoor relative humidity was as high as 90% during the peak period of 10.00 am to 4.00 pm, while model A was relatively at 62 % and model B was at 60 % as shown in Figure 9. This means that significant percentage of the available energy from electricity has been used for air cooling in model C as compared to mode A and B where lesser amount of energy was used for cooling. Moreover, given the recommended set indoor relative humidity of 60% with A/C, model B recorded better performance when compared with model A. This suggests better indoor thermal comfort conditions in model B in terms of indoor temperature and indoor relative humidity (as shown in Figure 8).

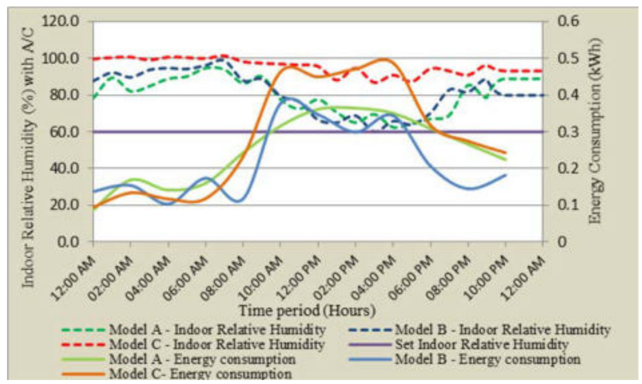

Figure 9. Energy and Indoor relative humidity

Figure 9 also shows the relationship between the outdoor relative humidity and the energy consumption. In this case, the outdoor relative humidity represents the percentage of the available energy for cooling. Figure 10 shows that between the periods of 12.00 am to 8.00 am, the average outdoor relative humidity of the three models was high ranging from 80 % - 100% while the energy consumption rate of the three models was low, ranging from 0.1 to 0.2 kWh. This means that the percentage of the available energy for cooling is very high between the periods of 12.00 am to 8.00 am.

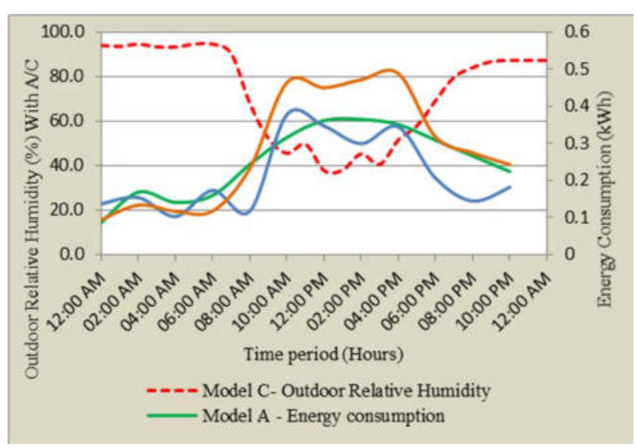

Figure 10. Energy and Outdoor relative humidity

Moreover, as the solar radiation increases, the outdoor temperature increases and the energy consumption also increases, while the outdoor relative humidity decreases. Thereby it reduces the available energy for cooling between the periods of 10.00 am to 6.00 pm. Within these periods, model B recorded the lowest energy consumption, compared to the other two models with 40% outdoor relative humidity. This means that Model B has more energy available for cooling than models A and C. This suggests that model B is more sustainable in terms of energy efficiency and relative humidity performance.

5.2 Energy Efficiency Performance of Insulated Roof Systems

From this data set, average energy consumption over a 24-hour period was computed. The results for the five (5) models in Figure 11 show relatively similar trend-lines for progression of energy consumption throughout the 24hrs time period. For the period 6-12 (morning) consumption consistently increased along exponential trends, peaking between 12 and 15 (midday to mid-afternoon), after which consumption gradually decreases along a gentler inverse exponential trend into the nighttime period, up to approximately 24 (midnight). Between 24 (midnight) and 30 (sunrise) consumption remains constant.

Considering the energy consumption for the 18-24 period, it can be inferred that the models still require a significant amount of cooling after sunset to achieve thermal acceptability of the internal environment. Moreover, with the aid of the thermal mass of the material components of the envelope, heat energy produced by the sun is absorbed and stored by the models during the day and released to the internal and ambient at night when external temperatures drop.

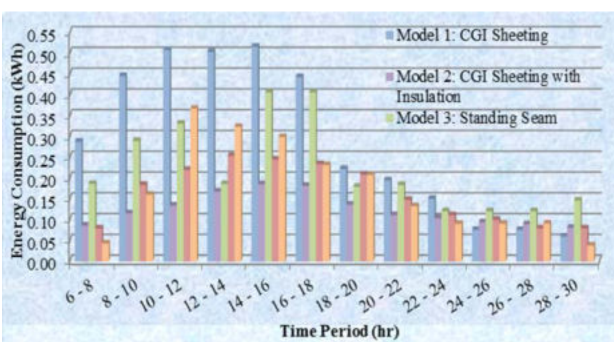

Figure 11. Average Energy Consumptions for Tested Roofing System over a 24-hr period

Besides, the consistency of consumption between 24 and 30 (midnight to sunrise) indicates that the heat source (building envelope) has dissipated most of the heat energy stored during the daytime period and a state of relative thermal equilibrium was achieved, thereby necessitating minimum and consistent function by the air conditioning. Further analysis of data presented in Figure 10 shows that the bulk energy consumption (approximately 60% - 70%) for each model was engaged during the 6-18 period (daytime period) where cooling requirements are most significant. Upon removal of an external heat source (i.e. the sun), the models, were seen to engage the remaining 30% - 40% of the total energy consumed for the 24 hr. period. This is attributable to lower external air and surface temperatures, and the relatively minimal heat gains from the environment.

In the case of the findings displayed in Figure 12 on the model energy consumption performance ranking, it can be seen from Figure 11 that daytime (6-18) consumptions for each model are consistently greater than those for the nighttime periods (18-30). Ranking of each model with respect to efficiency of cumulative energy consumption shows model 2 with corrugated galvanised sheeting roof system and insulation consumed the least energy and emerged the most efficiency. It can be seen in the cumulative energy consumption performance that the roofing systems with insulation (Models 2 and 4) are more energy efficient than their counterparts without while concrete (Model 5) that deemed a relative mid-range performance. Considering the insulated systems, Corrugated Galvanised Iron (C.G.I) (model 2) outperforms Standing Seam roofing system (model 4).

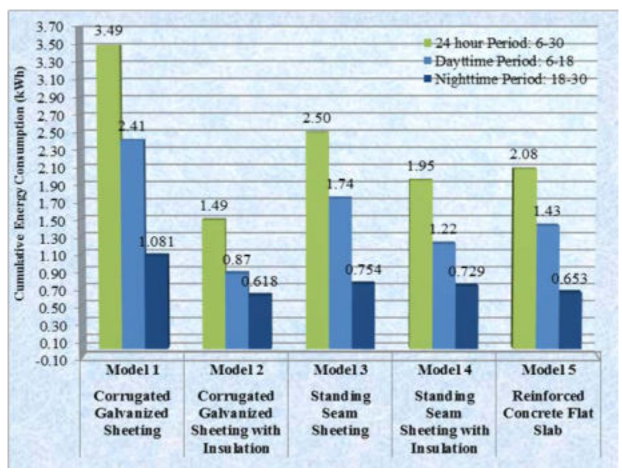

Figure 12. Cumulative average energy consumption for tested roofing systems

In Figure 13, the reverse is shown for the un-insulated counterparts as Standing Seam is proven to outperform the C.G.I. system. Moreover, in terms of the average rate energy consumption (Iwaro, 2016), Model 4 with standing seam sheeting roof system was more energy efficient than Model 2 with insulation. Energy consumption rates during the daytime period can be seen to be significantly greater than at night as the required cooling load is greater in the daytime than at night.

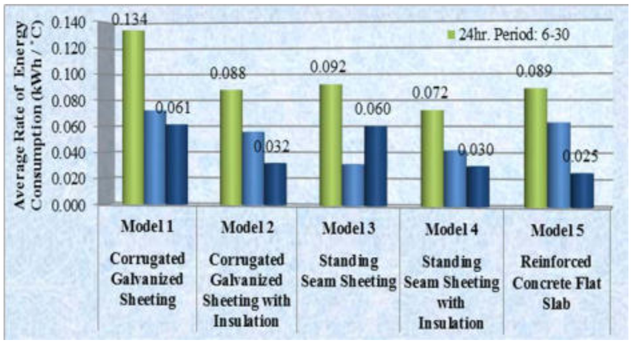

Figure 13. Average Rate of Energy Consumption for Tested Roofing Systems

Moreover, the energy consumption at night is not solely a function of required cooling load, but also minimum operating requirements of the air-conditioning. With respect to their energy efficiency (rate of energy consumption) the insulated roof systems are observed to outperform all other roof systems tested; Standing Seam with insulation (0.072 kWh/°C) followed by C.G.I Sheeting with Insulation (0.088 kWh/°C). Reinforced Concrete Flat Slab is deemed the mid- range performer (0.89 kWh/°C) followed by the un-insulated models, whereas with their insulated counterparts, Standing Seam (0.092 kWh/°C) was rated more efficient than C.G.I. (0.134 kWh/°C). Overall, both C.G.I Sheeting with Insulation and Standing Seam with insulation performed best in terms of impact on the building energy efficiency. These roofing systems can be recommended as effective and sustainable passive strategies for residential building energy efficiency.

6. Discussion

The difference in temperature between the external and internal environment for the tested envelope systems, without the function of air-conditioning is termed the "Baseline Thermal Variation". This value is a direct measure of the thermal efficiency of each building envelope system. The ability of the envelope system limits energy transference from the generally warmer to the cooler environment (along the temperature gradient); thus positively contributing to achieving acceptable levels of thermal comfort for the interior.

The baseline thermal variation is the amount by which the building envelope was able to keep the internal temperature cooler by in comparison to the external during the 6-18 (daytime) period and vice versa for the 18-30 (nighttime) period. Given external temperatures during the daytime within the upper limit or in excess of the acceptable comfort range, a decrease in temperature is deemed desirable.

Besides, ranking of Baseline Thermal Variations and energy consumption rate for the 6-18 (daytime) period for envelope roofing systems show that the insulated models proved the most thermally and energy efficient, with the Standing seam system with insulation (Model 4) followed by the C.G.I. System with insulation (Model 2) being the top performances, affecting the largest reductions of internal temperatures, more energy efficient and thermal acceptability. Reinforced concrete flat slab system (Model 5) was the middle performer, seeming to achieve a balance between the performance of the insulated and un-insulated metal sheeting systems. The un-insulated systems were observed to have affected the smallest temperature differentials, with the Standing Seam system (Model 3) outperforming the C.G.I. System (Model 1), which was the least efficient of all tested systems. The rated relative efficiencies of the envelope roofing systems were found to be in direct correlation, with the findings of the literature review (Sharma 2013) and subsequent theoretical calculation.

Moreover, the building envelope systems would function to limit the transference of energy from the warmer external ambient (presence of the sun) to the cooler interior during the 6-18 (daytime) period. However, during the 18-30 (nighttime) period, when external temperatures drop lower than the internal, the building envelope would function at the same rated efficiency but in reverse, limiting dissipation of the stored heat energy (attributable to the thermal mass of the model) from the internal to the external ambient.

Evidence of the consistent performance of each roofing system is evidenced as follows: for any model the magnitude of internal temperature decrease observed for the 6-18 (daytime) period, is near equal to the magnitude of internal temperature increase observed for the 18-30 (nighttime) period. It can thus be deduced that the insulation utilised for the metal sheeting systems provides beneficial thermal regulation during the daytime and has an inverse effect at night. For rating purposes, the 6-18 (daytime) period is determined to be the dominant efficiency rating of Baseline Thermal Variation, as it is given a heavier significance rating. The significance weighting of the 6-18 (daytime) period out ranked that of the 18-30 (nighttime) period. This is because the magnitude of external temperatures during the day was significantly higher than those at night. This meant that the effect of insulation was more critical towards achieving thermal efficiency during the 6-18 (daytime) period compared to the 18-30 (nighttime) period, where external temperatures are comparatively closer to achieving acceptable values for thermal comfort.

It is very important for passive housings and eco-friendly building concepts such as sustainable envelope, wall and roof passive strategies to be implemented. According to this study, the tested passive sustainable strategies have been found to be effective in the realisation of the building energy efficiency. Prominent among them include: Standing Seam roofing sheet insulated with fibre glass, corrugated galvanised roofing sheet insulated with glass fibre, reinforced concrete flat slab roof, concrete block wall internally insulated with fibre glass, clay block wall internally insulated with fibre glass, and building envelope systems insulated with fibre glass such as Clay block wall insulated with fibre glass, corrugated standing seam sheet insulated with fibre glass, Terrazo floor finishing, and 100mm concrete slab.

Based on the above analyses, these passive strategies were found to be the most effective energy saving strategies for realising building energy efficiency. According to Sharma (2013), there is over 50% energy saving potentials in building sector. As such, building sector should be considered as a potential sector to address the issues of global energy crisis and climate change. Besides, building worldwide is the main drive of the world economy and account for up to 40% of total energy use. The green building market in both the residential and non-residential sectors was estimated to have increased from \$36bn in 2009 to \$60bn by 2013 (Zhang and Cooke 2010). This shows that the market potential for green building is high.

It is important to implement sustainable passive strategies established in this study where the residential building energy efficiency, such as sustainable building envelopes, wall and roof passive strategies tested.

7. Conclusion

The findings derived from this study have proved that the utilisation of insulation in residential building envelope in warm humid regions, will significantly reduce heat transfer between the internal and ambient environment, thus reducing the energy demand of the structure and the relative carbon footprint of a structure per unit area over its lifetime. In addition, it has been proved that the utilisation of a flat slab concrete roofing system as opposed to the roof sheeting alternative systems, will be comparatively more cost effective for longer time and yield similar energy demand reductions.

In the short terms, insulated galvanised and standing seam roofing systems are more energy efficient and cost effective, while in the longer terms, flat slab concrete roofing system is more energy efficient and cost effective. Also, this study concludes that the fibre glass fibre insulated masonry walls, roofs and envelope can reduce the energy consumption associated with thermal cooling making structures more energy efficient. The insulated envelope model, walls and roof system recorded the lowest relative humidity, indoor temperature values and hence performed the best in terms of energy consumption. In addition, the energy consumption values of the models tested showed that the fibre glass insulation utilised less energy to achieve thermal comfort.

Hence, these results have showed that sustainable envelope, wall and roof passive strategies such as corrugated standing seam roof sheeting system with fibre glass insulation, corrugated galvanised roof sheeting system insulated with glass fibre, reinforced concrete flat slab roof, and insulated building envelope systems (Clay block wall insulated with fibre glass, corrugated standing seam sheet insulated with fibre glass, Terrazo floor finishing, and 100mm concrete slab) can be used to improve the energy efficiency of the residential building structures in hot dry climatic region. The implementation of these strategies is intended for low cost residential buildings in a hot dry climate.

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