THERMAL PERFORMANCE OF HEAVY-WEIGHT AND LIGHT-WEIGHT STEEL FRAME CONSTRUCTION APPROACHES IN THE CENTRAL PRETORIA CLIMATE

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Abstract

The purpose of this paper is to analyse the thermal performance of two buildings. The one has a large thermal mass and the other a highly insulated low thermal mass. A typical 120 m^2 suburban building was modelled in Ecotect. As part of the model infiltration rate, wind sensitivity and a central Pretoria weather file were used. New material composites were introduced in the materials database to represent typical building materials used in the construction of heavy and light-weight buildings in South Africa. The thermal characteristics of these new materials were then calculated within Ecotect. Ecomat was used to calculate thermal lag which was used as an additional input into Ecotect. The research indicates that a low thermal mass and highly insulated building have been shown to use 18.3% less annual space heating and cooling energy when compared to the high thermal mass building. The good thermal performance results of the light-weight building will help in clearing scepticism to adopting this construction technology in southern Africa where high thermal mass masonry is still predominant.

Keywords: heavy weight, thermal mass, light-weight building construction, thermal performance, energy efficiency

1. INTRODUCTION

Developing countries have a great need to construct large numbers of houses and social infrastructure in a cost-effective and rapid way while maintaining acceptable, habitable conditions. Recently, new construction methods such as light steel frames (LSFs) that are light-weight and highly insulated have been introduced in South Africa. Currently heavy-weight, high thermal mass masonry is still the most common construction material.

At the moment LSFs in South Africa (Figure 1) is slowly being accepted by the construction industry. There is much scepticism in its adoption though the practice has been applied for decades in Europe, Australia and the United States[1]. The general view within the construction industry is that an increase in thermal mass will result in a decrease in space heating and cooling loads in buildings.

[1]http://www.sasfa.co.za/ accessed 25 July 2011

Figure 1: Illustration of the different construction technologies of light-weight highly insulated (left) and heavy-weight high thermal mass.

Many myths exist regarding methods to improve the thermal performance of buildings. For example, it is assumed that an improvement in insulation or the introduction of more thermal mass will improve the thermal performance of a building. It is the aim of this paper to resolve the conflicting views on the contribution of building thermal mass and building insulation on building thermal performance.

2. BUILDING INFILTRATION RATE MEASUREMENTS

Concentration decay of carbon dioxide (CO2) tracer gas was used to measure the infiltration rate for a light-weight highly insulated building on the CSIR Built Environment Innovation Site. CO2 was injected into the house. The windows and doors were closed during the tracer gas tests and then dispersed by a mixing fan to ensure uniformity of concentration as stipulated by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) Fundamentals handbook, 1997. A SENTRY ST-303 non-dispersive infrared gas sensor was used to monitor indoor CO2 concentration. The CO2 sensor was placed at a height of 0.45 m above the finished floor level. This height was used to take account of infiltration underneath doors as well.

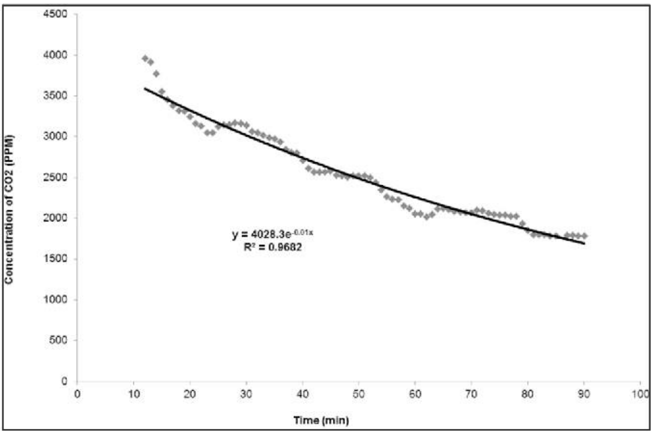

Figure 2: Tracer gas concentration decay for the LSF building at with the CSIR Built Environment Innovation Site.

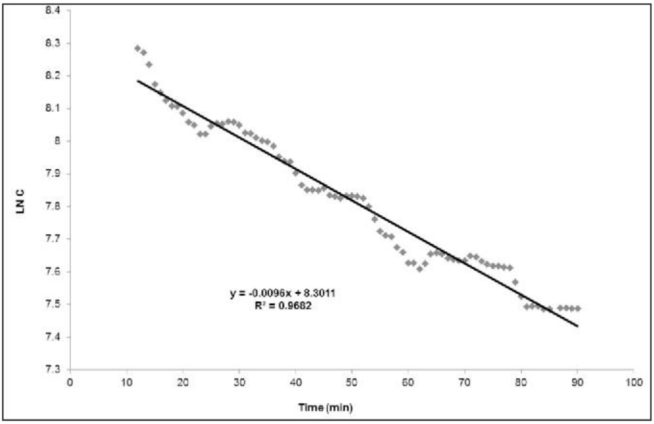

Figure 3: logarithmic graph of CO_2 concentration versus time

According to the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) Fundamentals handbook, 1997, the carbon dioxide decays exponentially (assuming perfect mixing) and at any time θ is given by the following expression:

$$C(\theta) = C_o e^{I\theta} \qquad (1)$$

Where

I	is the air change rate per hour
C	is the concentration of CO_2
θ	is time
C_o	is the concentration of CO_2 at $\theta = 0$.

If logarithms are applied to both sides of equation (1), the equation becomes: $C(\theta) = In\ C_o - I\theta$, and differentiating with respect to time , the air exchange rate per minute can be approximated by the gradient of the linear regression straight line of best fit as illustrated in Figure 3.

From Figure 3 the gradient from the linear equation is 0.0096 AC/min and to calculate the numbers of air changes per hour, this gradient was multiplied by 60 (since the time record was in minutes) and this gives 0.57 air changes per hour (ACH).

3 BUILDING MODELLING

3.1 Ecotect thermal analysis programme

The Ecotect building thermal analysis programme was used for the thermal performance analysis.

Ecotect was selected for the analysis because it is capable of performing a wide range of building analysis calculations within an interactive three-dimensional environment. Other comparable software programmes such as EnergyPlus tend to rely on text-based[2] input, or only perform a limited range of analysis calculations Marsh[3] (n.d.) measured indoor air temperature for a passive building and then modelled the building in Ecotect, Energy plus and HTB2 simulation programmes. The results obtained from Ecotect were in very close agreement with corresponding measured temperature when compared to EnergyPlus and HTB2 results which differed, though showed similar correlation with the measured results. Similar studies done by Makaka, Meyer and McPherson (2008) showed good agreement between predicted indoor temperatures from Ecotect and measured indoor temperatures. Therefore for a passive thermal performance analysis of buildings, results from Ecotect can be considered adequate to inform passive energy-efficient building design.

3.2 Ecotect model

The two thermal models for the suburban building of 120 m^2 for the heavy weight and light-weight construction were modelled in Ecotect (Figure 4). The two models have different wall compositions. The heavy-weight wall consists of 15 mm cement plaster on the outside, 220 mm normal fired clay brick and 15 mm cement plaster on the inside. The light-weight wall consists of 9 mm fibre cement sheet, 0.2 mm vapour membrane, 30 mm OSB board, 102 mm glass wool insulation in combination with 0.8 mm steel studs and 15 mm gypsum board in combination with light steel frames (Table 2). All the other construction elements are identical.

Parameters such as floor area, ceiling height, arrangement of zones and orientation are also identical.

The materials database of Ecotect was updated to represent the composites for the typical building materials used in the construction of heavy weight and light weight-buildings in South Africa. The thermal property values such as U-value, thermal decrement, admittance, solar absorption and visible transmittance for these materials were calculated by means of Ecotect. Unfortunately Ecotect cannot calculate thermal lag for user-defined materials. To address this shortcoming Ecomat was acquired and used for this purpose. Ecomat calculates thermal lag according to the method in the EN ISO 13786:2007 standard. This method corresponds with the Chartered Institution of Building Services Engineers (CIBSE) Admittance Method, which is the method used by Ecotect for its thermal calculations[4]. The two models had the same geographical location (Pretoria) and was north facing. The latitude and longitude for Pretoria are 25.5° S and 28.1˚ E, respectively.

[2]EnergyPlus has been interfaced with Google Sketchup that makes it more convenient to use.
[3]http://www.ecotect.com/node/2077, accessed 18 January 2010
[4]http://www.ecoeficiente.es/ecomatHelp/index.htm?Features.html, accessed 25 November 2009.

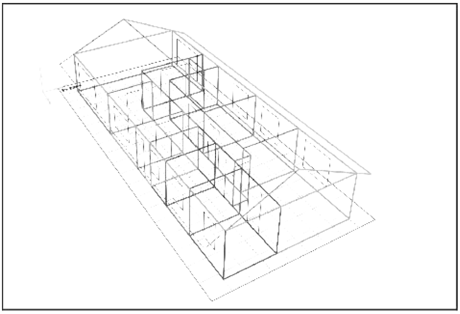

Figure 4: 3-Dimensional perspective view of the Thermal model, with individual colour for each zone developed in Ecotect.

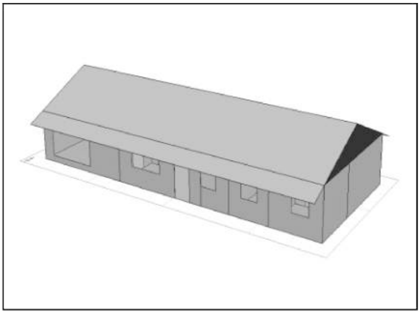

Figure 5: Visual three-dimensional thermal model showing southern and eastern facades developed in Ecotect.

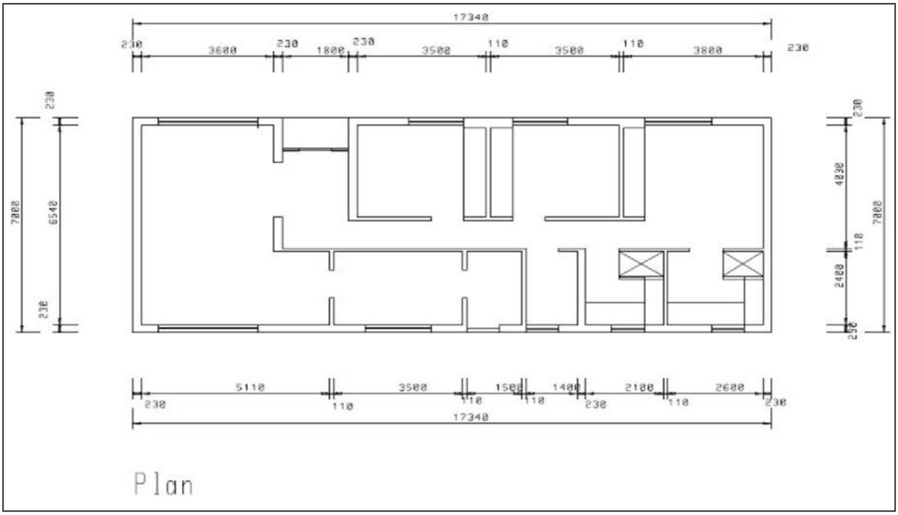

Figure 6: Building plan used in thermal analysis.

3.3 Considerations in the model

3.3.1 Building material thermo-physical properties

Due to the large differences in the thermal conductivity of the steel used in combination with glass-wool thermal insulation within the wall structure of the LSF building, a limited amount of thermal bridging occurs. In this paper the British, European and International Standard (BS EN ISO) 6946:1997 U-value calculations procedure as used by Doran and Kosmina (1999) was used to calculate the U value of the LSF building's internal and external walls to take thermal bridging into account.

Other building material thermal properties such as density, specific heat capacity and conductivity were obtained from the Ecotect materials library, South African Light Steel Association and from the publication by Clarke, Yaneske and Pinney (1990).

3.3.2 Zones

A thermal zone is defined in Ecotect as a homogenous enclosed volume of air. In most cases this corresponds to a single room. It is assumed that the air within a zone is able to mix freely. Each of the rooms was defined as distinct thermal zones. This was done to simulate and quantify the thermal exchanges between the rooms.

Table 1 shows the total area, surface area, floor area and volume for all the thermal zones calculated with Ecotect. These values are important because the volume of air circulating within each of the thermal zones will have a large impact on the resultant indoor temperature and also on the amount of heating or cooling energy required to maintain the indoor environment within thermal comfort. The total surface area (second column Table 1) represents the total surface area through which heat transfer occurs. Row 12 of Table 1 shows that the total floor area of the models is 119.545 m2 and the total volume of air within all the zones is 286.983 m3 excluding the roof.

Table 1: Zone areas and zone volumes for the LSF and masonry houses as calculated in Ecotect.

Zone	Total surface area (m^2)	Floor area (m^2)	Volume (m^3)
Dining/lounge	124.217	32.229	77.521
Passage	89.093	13.088	31.169
Bedroom 1	60.365	12.902	30.966
Bedroom 2	57.715	12.130	29.143
Bedroom 3	73.018	16.619	39.875
Bathroom en-suite	42.244	7.754	18.651
Bathroom	35.871	6.055	14.565
Toilet	29.908	4.466	10.743
Laundry	29.703	4.411	10.611
Kitchen	50.263	9.891	23.739
Sub-total	**592.397**	**119.545**	**286.983**
Roof zone	299.158	121.380	88.165
Total	**891.555**	**240.925**	**375.148**

3.3.3 Internal gains

Internal heat gains occur due to occupancy, lighting and equipment. In order to assess and compare the passive thermal performance of both construction methods, the value for internal gains was assigned as zero in each of the thermal zones. This was done to assess the pure comparative passive thermal performance without interference from other complicating factors.

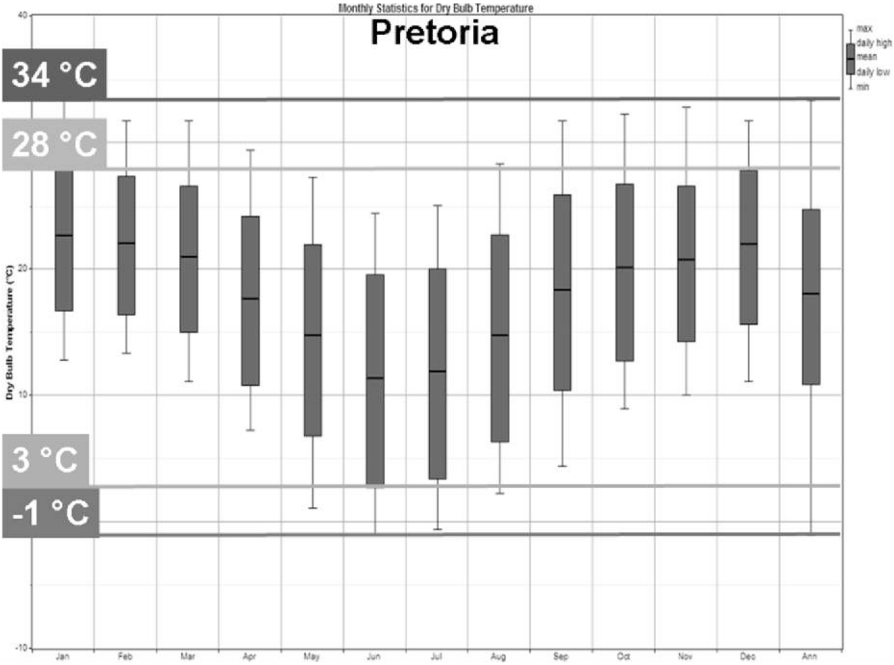

Figure 7: Illustration of annual average temperatures for Pretoria, South Africa obtained from Climate advisor software.

3.3.4 Operation schedule

An identical 24-hour operational schedule was assumed for the two models to assess the diurnal thermal performance.

3.3.5 Infiltration

The infiltration rate is measured in ACH and specifies air leakage within the zone through cracks and gaps. The quality of the workmanship during construction greatly influences this. This rate ranges from 0.25 ACH for air tight buildings to 2.0 ACH for leaky ones in Ecotect. CO2 tracer gas tests carried out at the CSIR yielded a 0.57 ACH infiltration rate. In this analysis an infiltration value of 0.57 ACH for all the thermal zones in the two models was assumed.

The infiltration value (0.57 ACH) was assumed to be the same for the two simulations mainly for strict comparative purposes. In reality infiltration rate is dependent on workmanship and building quality and would be different for each housing unit.

It is important to specify wind sensitivity, which means sensitivity of the zone to wind speed according to a specified sheltering level. This is an additional air change rate value, over and above the base infiltration rate. Ecotect sets wind sensitivity to 0.1 ACH when the building is wind-sheltered and 1.5 ACH when the building is exposed to wind. In this report a wind sensitivity of 0.1 ACH was assumed in all the thermal zones. It was assumed that surrounding buildings provide some sheltering as is the case on the CSIR Built Environment Innovation Site.

Table 2: Detailed description of the light-weight highly (insulated) and high thermal mass buildings.

Element	Light weight	Heavy weight
Roof	30 mm concrete tiles[5], 38 mm Air gap, 0.2 mm polyethylene (high density). U_{value}= 2.59 $W/m^2.K$, Thermal lag = 0.82 hrs	30 mm concrete tiles, 38 mm Air gap, 0.2 mm polyethylene (high density). U_{value}= 2.59 $W/m^2.K$, Thermal lag = 0.82 hrs
External walls	9 mm fibre cement sheet, 0.2 mm vapour membrane, 30 mm OSB board, 102 mm glass-wool insulation in combination with 0.8 mm steel studs, 15 mm gypsum board. U_{value}= 0.5402 $W/m^2.K$, Thermal lag = 2.6 hrs	15 mm cement plaster, 220 mm brick normal fire clay, 15 mm cement plaster. U_{value}= 2.72 $W/m^2.K$, Thermal lag = 6.05 hrs
Internal walls	9 mm fibre cement sheet, 0.2 mm vapour membrane, 30 mm OSB board, 102 mm glass-wool insulation in combination with 0.8 mm steel studs, 15 mm gypsum board. U_{value}= 0.5402 $W/m^2.K$, Thermal lag = 2.6 hrs	15 mm cement plaster, 110 mm brick normal fire clay, 15 mm cement plaster. U_{value}= 3.54 $W/m^2.K$, Thermal lag = 3.24 hrs
Ceiling	140 mm glass-wool insulation, 6.4 m m gypsum board. U_{value} = 0.26 $W/m^2.K$, Thermal lag = 0.44 hrs	140mm glass-wool insulation, 6.4 mm gypsum board. U_{value} = 0.26 $W/m^2.K$, Thermal lag = 0.44 hrs
Floor	75 mm concrete 1-4 dry, 10 mm cement screed. U_{value}= 3.51 $W/m^2.K$, Thermal lag = 2.15 hrs	75 mm concrete 1-4 dry, 10 mm cement screed. U_{value}= 3.51 $W/m^2.K$, Thermal lag = 2.15 hrs

3.3.6 Thermal comfort band

The temperature comfort band for an air-conditioned building used in this study is 20˚C to 24˚C as recommended in the South African National Standards (SANS) 204: 2011. For this study, this range was used for all the thermal zones. Zones are artificially assumed to be air conditioned in order for Ecotect software to be able to calculate heating and cooling loads.

[5]Order of material layers is from outside to inside

4. ANALYSIS AND DISCUSSION OF RESULTS

4.1. Indoor temperature for the two constructions during the hottest day

The graphs in Figures 8 to11 show the indoor temperature variations for all the thermal zones of the high thermal mass and light-weight buildings for the hottest and coldest days. Temperature is shown in the vertical axis and time of day in the horizontal axis. These graphs were generated by Ecotect using the following settings and assumptions:

I. The type of system was set to none for all the thermal zones of the two models. This means no heating and cooling as well as no ventilation air coming in through opened windows and doors except infiltration air.

ii. The sensible and latent heat loads were assumed to be zero (for all the thermal zones of the two models which means that there are no internal heat gains due to lighting and equipment).

The purpose of abovementioned was to perform a comparison under simplified passive conditions.

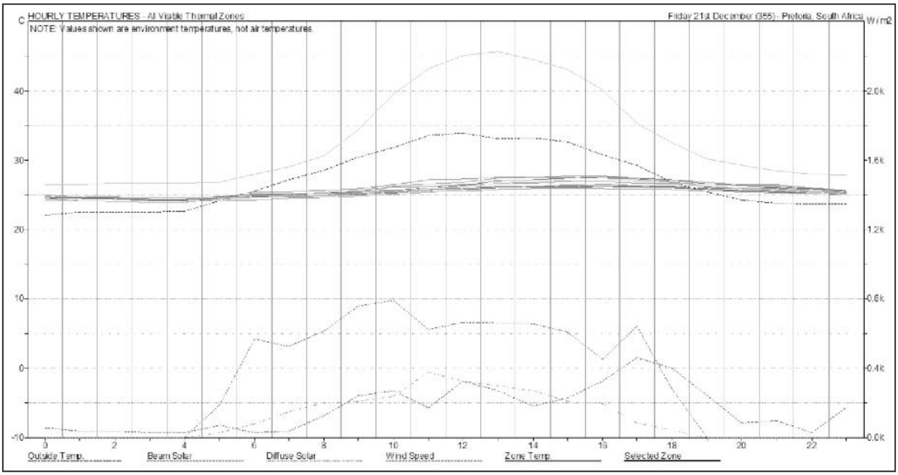

Figure 8: Indoor hourly temperatures for high thermal mass building for the hottest day (graph generated by Ecotect).

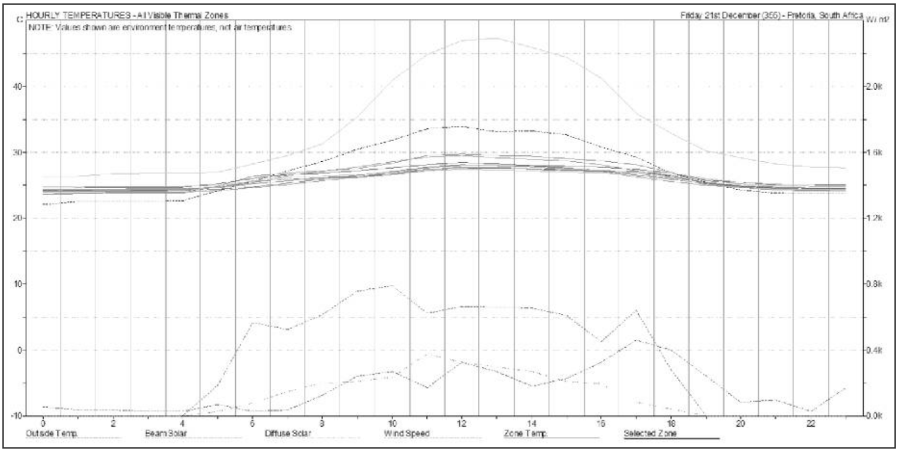

Figure 9: Indoor hourly temperatures for light-weight highly insulated building for the hottest day (graph generated by Ecotect).

Figure 8 shows that on the hottest day, the highest average indoor temperature for the thermal zones of the high thermal mass building is 27.6 ˚C and the lowest average indoor temperature is 24 ˚C. The temperature swing (maximum indoor temperature – minimum indoor temperature) is 3.6 ˚C per day. The indoor temperature line graphs of the thermal zones of a high thermal mass building do not follow the trend of the outside temperature graph as indicated with the blue dashed line graph. This line is almost horizontal. This can be attributed to the so-called flywheel indoor temperature damping provided by the high thermal mass of the masonry walls that act as a heat sink. Figure 9 shows that on the hottest day, the highest average indoor temperature for all the thermal zones of the light- weight highly insulated building is 29.8 ˚C and the lowest average indoor temperature is 23.6 ˚C. The temperature swing (maximum indoor temperature – minimum indoor temperature) is 6.2 ˚C per day. This is higher than that of the high thermal mass building. This can be attributed to the low thermal mass and heat storage capacity of the light-weight building.

The difference between the upper comfort limit temperature and the indoor temperatures is larger in the light-weight building than in the high thermal mass building. This explains the high cooling energy requirement for the light-weight building of 14.9 GJ per annum (Figure 16) when compared to high thermal mass building that requires only 11.5 GJ per annum (Figure 15).

4.2 Indoor temperature for the two constructions during the coldest day

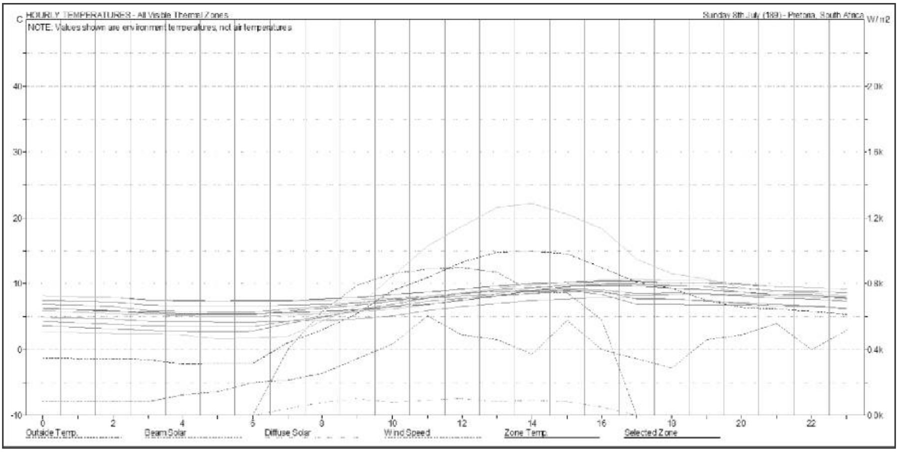

Figure 10: Indoor hourly temperatures for the high thermal mass building for the coldest day (graph generated by Ecotect).

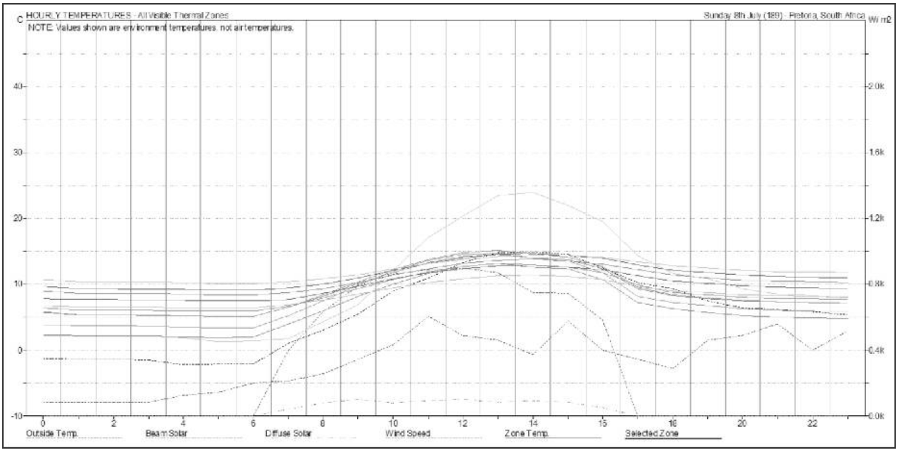

Figure 11: Indoor hourly temperatures for the light-weight highly insulated building for the coldest day (graph generated by Ecotect).

Figure 12: Key for graphs Figure 8-11 (the colours in the key matches the colours on the graphs).

Figure 10 shows that for the coldest day, the highest average indoor temperature for the thermal zones of the high thermal mass building is 9 ˚C and the lowest is 2.7 ˚C. This gives a temperature swing (maximum indoor temperature – minimum indoor temperature) of 6.3 ˚C. The indoor temperature line graphs of all the thermal zones of the high thermal mass building do not follow the trend of the outside temperature graph as indicated with the blue dashed line graph. This line is fairly horizontal. This can be attributed to high thermal mass provided by masonry walls which tend to absorb heat from the space and from outside.

Figure 11 shows that for the coldest day, the highest average indoor temperature for all the thermal zones of the light-weight building is 13.1˚C and the lowest is 1.9˚C. This gives a temperature swing (maximum indoor temperature – minimum indoor temperature) of 11.2˚C. This temperature swing is higher than that of the high thermal mass building. This can be attributed to the low thermal mass of the light-weight highly insulated building. It should be noted that the average indoor temperature difference between the lower comfort limit temperature and the indoor temperatures is larger in the high thermal mass building than the light-weight building. This explains the high heating energy requirement for the high thermal mass building of 39.4GJ per annum (Figure 15) when compared to the light-weight building that requires 26.6 GJ per annum (Figure 16).

The general trend of indoor temperature variation compared with outdoor temperature variation for summer and winter as shown in Figures 8 to 11 agrees with the trend of measured indoor temperature variation with outdoor temperature variation observed by Van Straaten, 1967, pp 87-88. The objective of his study was to compare the temperature variation in a light-weight structure (timber frame) with those of masonry structure.

4.3 Thermal comfort charts for the two constructions

Figures 13 and 14 show number of hours in discomfort (horizontal axis) and the month of the year (vertical axis). The red bars show the proportion of time when people will feel hot and the blue bars show the proportion of time when the people will feel cold.

In order for Ecotect to calculate discomfort times, it requires for each of the passive thermal zones of the models to be occupied. In order to achieve this comparison each of the thermal zones of the two models were assumed to be occupied by one person.

The height of blue bars from April to August is shorter for the light-weight building (Figure 14) when compared to the corresponding blue bars for the high thermal mass building (Figure 13). This shows that during winter the levels of discomfort are lower in the light-weight highly insulated building when compared to discomfort levels in the high thermal mass building.

The height of red bar graphs during the summer months (September to April) is larger for the light-weight highly insulated building when compared to the high thermal mass building. This shows that occupants in the light-weight building experience a higher number of hot hours when compared to occupants of the high thermal mass building. This result confirms the over-heating problem of light-weight structures reported in literature.

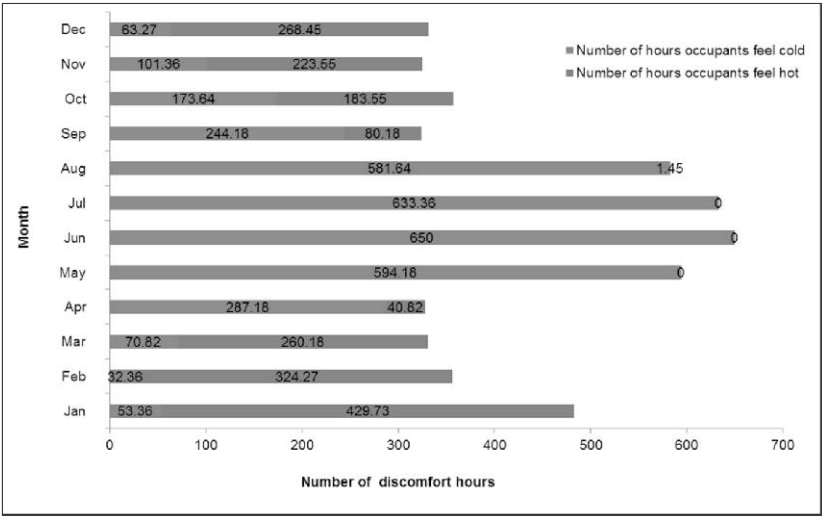

Figure 13: Annual discomfort periods for the high thermal mass building

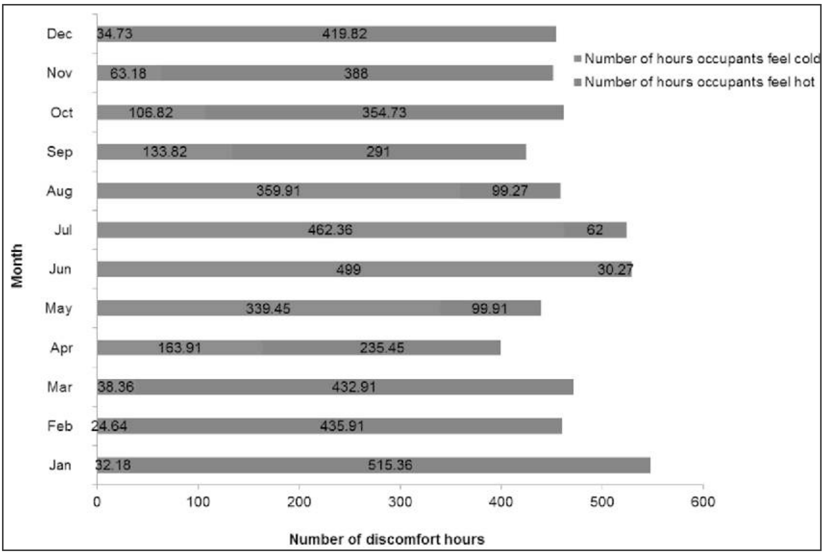

Figure 14: Annual discomfort periods for the light weight building

Considering 8 760 hours in a year, the indoor temperature of the high thermal mass building was outside of the thermal comfort temperature for 5 297.5 hours. The number of comfort indoor temperature hours for the high thermal mass building was thus 3 462.5 hours. This is 40% of the total number of hours in one year.

For the light-weight building the indoor temperature was outside of the thermal comfort temperature for 5 623 hours. Therefore, the number of comfort indoor temperature hours for the light-weight building was 3 137 hours. This is 36 % of the total number of hours in one year.

The high thermal mass building thus performs 4% better in terms of thermal comfort when compared to a light-weight highly insulated building.

4.4 Heating and cooling loads for the two constructions

In order to assess the thermal performance (in terms of heating and cooling loads), the type of system was switched on to full air-conditioning for all thermal zones of both models, excluding the roof thermal zone since there is no occupancy within the roof zone. This was done to calculate cooling and heating energy that is required in order to keep each of the two constructions within the thermal comfort temperature limits of 20 ˚C to 24 ˚C.

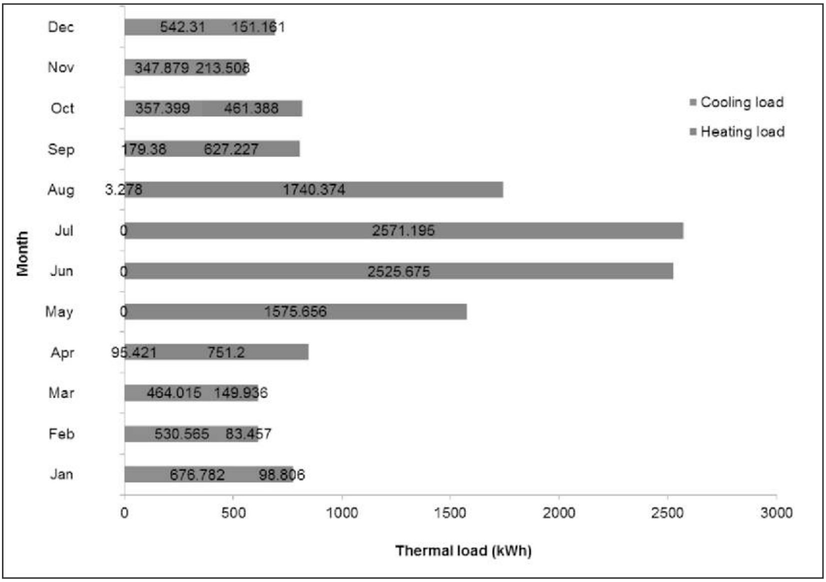

Figure 15: Heating and cooling load for the high thermal mass building (calculated by Ecotect)

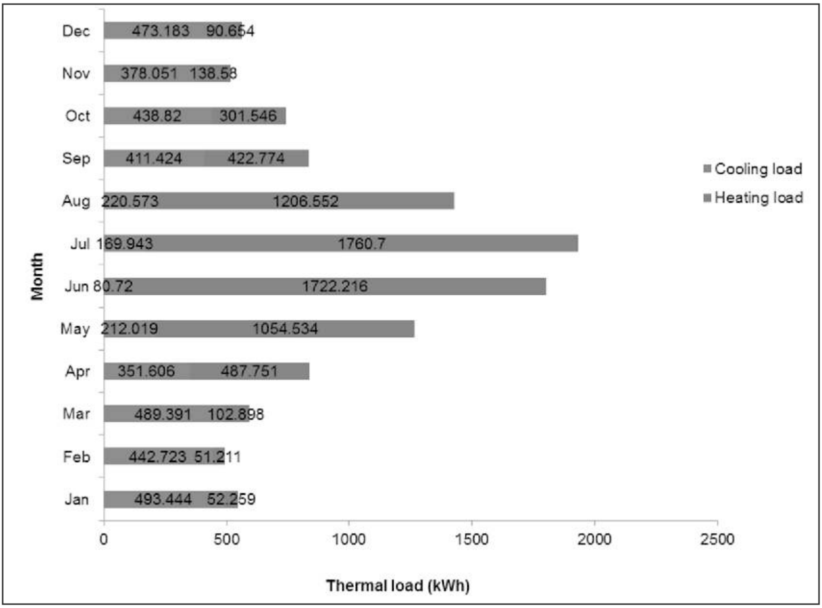

Figure 16: Heating and cooling load for the light weight building (calculated by Ecotect)

Due to a very narrow thermal comfort band for an air-conditioned building of 20˚C to 24˚C as stipulated by SANS 204: 2011, some heating requirements are seen to occur for both of the constructions even during the summer months (Figures 15 and 16). Further simulation results which are not shown in this paper predicted indoor temperatures of less than 20 ˚C during the summer months. This explains the heating during the summer months.

The high thermal mass building requires a total heating plus cooling load of 14 146 612 Wh (14 146.612 kWh) (50.9 GJ).

The light-weight highly insulated building requires a total heating plus cooling load of 11 553 569 Wh (11553.569 kWh) (41.5 GJ). In this case it shows that the light-weight building performs 18.3% better in terms of energy requirements to maintain thermal comfort conditions.

5. CONCLUSIONS AND RECOMMENDATIONS

The results show a high indoor temperature swing in the light-weight building when compared to the high thermal mass building. High indoor temperature swing is related to high thermal response. The implication of this is that the light-weight building cools down quickly after sunset which is beneficial during summer especially in bedrooms, and heats up quickly after sunrise which is beneficial during winter.

This paper indicated that for Pretoria, the light-weight building has a better winter thermal performance in terms of heating loads, indoor temperature and thermal comfort than the conventional masonry house. Results from this paper confirmed that the high thermal mass building has better thermal performance in terms of cooling loads, indoor temperature and thermal comfort during summer in comparison to the light-weight highly insulated building.

Szokolay (2000) concluded that high thermal mass and light-weight buildings have similar thermal performance. He goes on to say that there are other important attributes than just thermal mass that contribute to good thermal performance. Conradie (2013) gives a comprehensive guideline of the potential of building passive design strategies in various South African climatic regions.

Eskom, the electricity provider in South Africa, reported high peak demands for domestic use during winter months in comparison to summer months. The high winter demand may be attributed to the need for high space heating energy during winter. Therefore a light-weight building which requires less heating energy during winter months can contribute significantly to lowering peak electricity demand during winter. This peak reduction in electrical energy consumption is in line with the South African energy policy.

Since the insulation approach has benefits during winter and the thermal mass approach has benefits during summer, coupling the two in a single building design can optimise the thermal performance of both constructions. Recent studies focus on encapsulating phase change materials (PCM) into gypsum wallboards of light-weight structures. The wall boards compensate for the low heat storage capacity of light-weight buildings (Huang, Eames and Hewitt, 2006 and Sharma, et al., 2009).

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