Thermal mass vs. insulation building envelope design in six climatic regions of South Africa

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1 Introduction

Experience shows that there are a number of building design traps that are very tempting for designers. A typical example of this is that insulation is the answer to all thermal problems. The addition of insulation without attention to thermal mass and air infiltration will not only cause additional expenditure but also worsen indoor conditions. Quite often a lot of thermal mass is seen as the answer. Lots of mass reduces the temperature swing towards the average temperature which may be either too high or too low for comfort. This implies that mass must be considered together with night cooling or solar heating (Holm, 1996).

Heating, ventilation and air-conditioning (HVAC), contribute an estimated 5 400 MW to electricity demand in peak periods in South Africa. This is approximately 15% of South Africa's current peak demand consumption. On an annual basis, HVAC accounts for some 4 000 gigawatt hours of electricity consumption in South Africa (ESKOM, 2010).

Buildings' air conditioning loads arise from energy that flows into a building through its envelope, solar gains through windows, infiltration, and ventilation bringing in outside air that needs to be cooled and or dried, plus heat and moisture that are generated within the building (Duffie et al., 1980).

Better design of new buildings could result in a 50-75% reduction in their energy consumption (Clarke, 2001). Appropriate interventions in the existing building stock would reduce energy use significantly. Added together, this could significantly reduce the nation's energy bill and positively contribute to environmental impact and climate change mitigation. This would also help to alleviate the stressful indoor conditions experienced by many citizens. Indeed energy efficiency may be likened to an untapped, clean energy resource of vast potential (Clarke, 2001).

This chapter aims to evaluate the impact of thermal mass and high insulation (R-value) building envelope on energy consumption (space heating and space cooling) in six South African major cities using a building thermal simulation programme (*Ecotect*™ V 5.6).

2 Thermal mass and insulation

Insulation and thermal mass are similar in that they both slow down the movement of heat between exterior and interior spaces, but they are also different with respect to other characteristics.

High density materials such as concrete, brick, tiles, earth and water require a significant amount of heat to increase their temperature. They also lose heat slowly and are referred to as having a high thermal mass. In contrast low density, lightweight materials such as insulators (high Rvalue materials) require little heat to increase their temperature but also lose heat rapidly. The latter are referred to as low thermal mass materials. A material suitable for thermal mass must have:

- high heat capacity
- high density
- low reflectivity (i.e. a dark, or textured finish).

It is clear that thermal mass is not the same as insulation, which, in building terms, describes a building's ability to reduce the conduction (or flow) of heat between indoors and outdoors. The term thermal mass is used by Goulart (2004) to describe a building's overall capacity to store and release heat. In general, it is contained in walls, partitions, ceilings and floors of the building, which are constructed of materials of high heat capacity.

3 Methodology

The methodology adopted to investigate aforementioned included inter alia infiltration rate measurements, development of the *Ecotect* simulation model and simulation of houses with base case characteristics and energy efficient measures in six South African cities.

3.1 Building infiltration rate measurements

High infiltration rates means a leaky building meaning the beneficial effects of insulation are destroyed. Tracer gas tests were used to measure the infiltration rate for a light steel frame (LSF) house which was built on the CSIR building performance laboratory test site. Carbon dioxide was injected into the house with windows and doors closed during the tracer gas tests. The dilution was monitored over time (See Figure 1) to determine how quickly the gas dissipates through the house's leaky envelope. A non-dispersive infra-red absorbance (NDIR) gas sensor was used to monitor indoor carbon dioxide concentration. The carbon dioxide sensor was placed at height of about 0.45 m above the finished floor level. This height was used to take account of infiltration underneath doors as well.

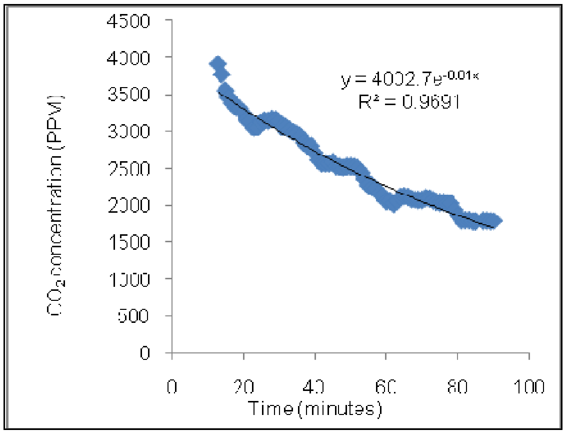

Figure 1:Tracer gas concentration decay for the whole 40 m^2 LSF house at the CSIR building performance laboratory

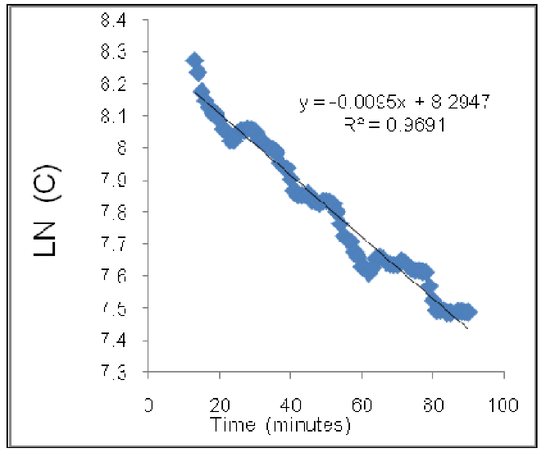

Figure 2: logarithmic graph of CO_2 concentration versus time

According to the ASHRAE (1997) fundamentals Handbook the carbon dioxide decays exponentially (assuming perfect mixing) and at any time t is given by the following expression:

$$C(\theta) = C_o e^{-I\theta} \quad \text{.......... (1)}$$

Where I is the air change rate per hour
C is the concentration of carbon dioxide
θ is time
C_o is the concentration of carbon dioxide at θ = 0.

Taking logarithms both sides of Eq. (1), the equation becomes:

$\ln C(\theta) = \ln C_0 - I\theta$, and differentiating with respect to time (θ) the air exchange rate (in minutes) can be approximated by the gradient of the linear regression straight line of best fit as illustrated in Figure 2.

From Figure 2 the gradient from the linear equation is 0.0095 Air Changes (AC) per minute. 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).

3.2 Building modelling

The construction details for each of the two houses were modelled using *Ecotect*. Weather files for Pretoria, Bloemfontein, Cape Town, Durban, Musina and Kimberley South Africa were uploaded in the software model. These cities were chosen because they represent different climatic regions as shown on the Köppen Geiger map (Green building Handbook, Volume 4, 2011. Chapter 12). Two models (virtual scientific representation of the two construction methods used to run comparative predictive simulations) were prepared for the two houses detailed in Figures 3 and 4, using the plan measurements detailed in Figure 5. The two base case models used different structural construction technologies for their walls. The masonry house used clay bricks for heavy weight and consequently high thermal mass. The LSF house used light steel frames in combination with glass wool for a light weight or high R-value type model in accordance with SANS 517 (see detail of construction detail in Table 2). All parameters such as floor area, ceiling height, arrangement for zones and orientation for the two models were identical. Some new material composites were introduced in the materials database to represent typical building materials used in the construction of heavy weight and light weight buildings in South Africa. The thermal property values (U-values, thermal decrement, admittance, solar absorption and visible transmittance) for these composites materials were calculated. One of the shortcomings of *Ecotect* when creating new material composites is that it is not able to calculate thermal lag for user defined materials. To address this shortcoming *Ecomat*™ v1.0 software was acquired and used for this purpose. *Ecomat* calculates thermal lag according to the EN ISO 13786:2007 standard. The standard is termed “Thermal performance of building components - Dynamic thermal characteristics - Calculation method (ISO 13786:2007).” This method corresponds with CIBSE Admittance Method, which is the method used by *Ecotect* for its thermal calculations.

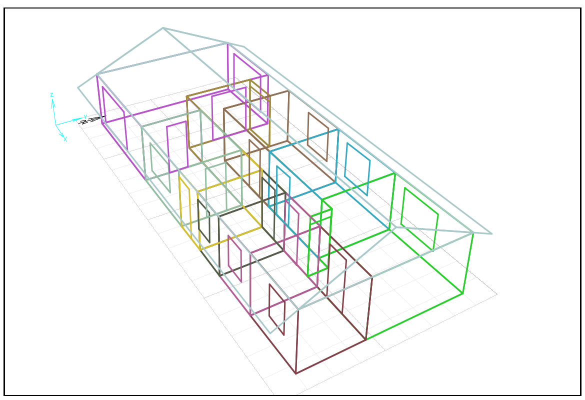

Figure 3: 3-Dimensional perspective view of the Thermal model, with individual colour for each zone developed in Ecotect V 5.6.

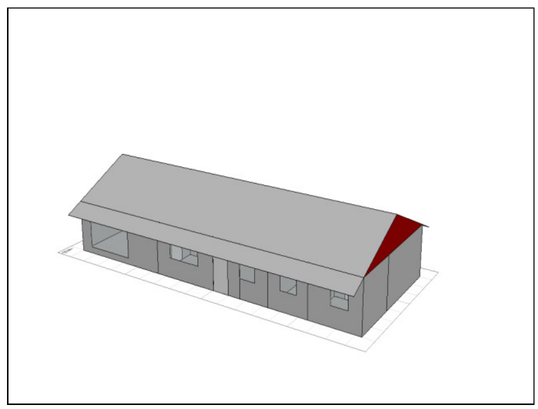

Figure 4: Visual 3-Dimensional thermal model showing Southern & Eastern facades developed in Ecotect V 5.6.

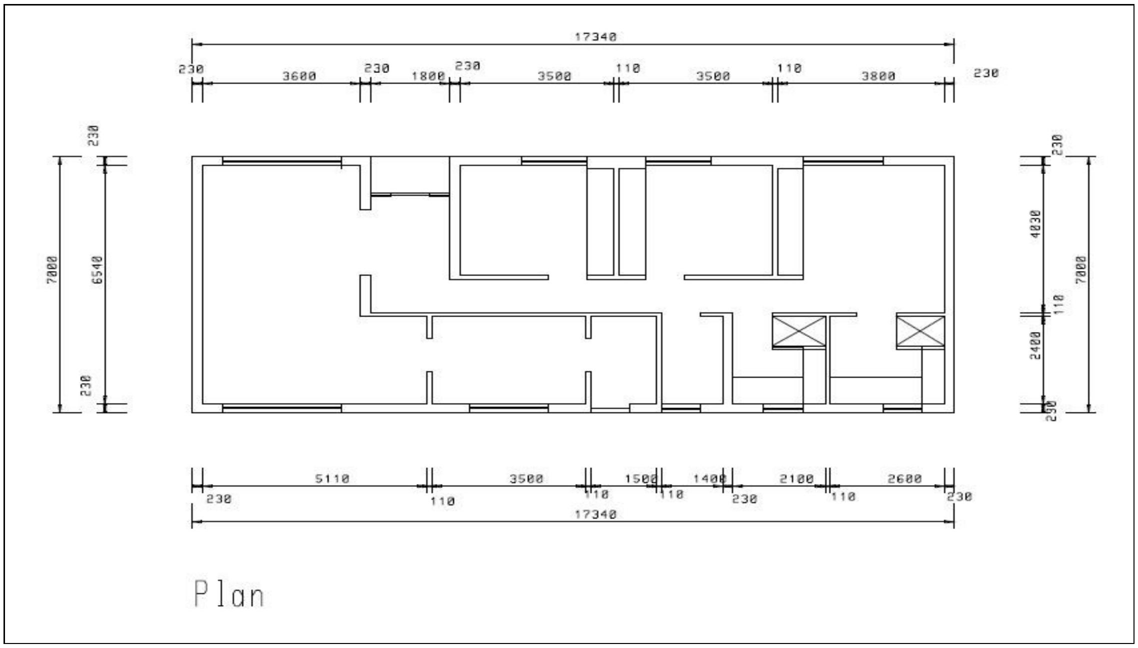

Figure 5: Residential building plan used in thermal analysis.

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 light steel house a limited amount of unavoidable thermal bridging occurs. In this study the BS EN ISO 6946:1997 Uvalue calculations procedure (Doran and Kosmina, 1999) was used to calculate the U-value of the light weight house internal and external walls taking the 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 Clarke et al., 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. Every room in the simulation model was defined as distinct thermal zone. This was done to simulate and quantify the thermal exchanges between the rooms. Table 1 shows the total area that includes surface areas, floor areas and volumes for all the thermal zones of both houses. These values were 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. The total area (second column Table 1) represent the total surface areas through which heat transfer occurs. Row 12 of Table 1 shows that the total floor area for each of the houses is 119.545 m^2 and the total volume of air that can be enclosed within all the Zones is 286.983 m^3, excluding the roof.

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

Zone	Total 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 the light weight and heavy weight houses, the value for internal gains was assigned as zero in each of the thermal zones for both houses. This was done in order to assess the pure comparative passive thermal performance of the envelope of the two houses without interference from other complicating factors.

3.3.4 Infiltration

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 for leaky ones in the *Ecotect* software. Carbon dioxide tracer gas tests carried out at the CSIR Building Performance Laboratory yielded 0.57 ACH (infiltration rate) for a light weight 40 m^2 test house. In this analysis an infiltration value of 0.57 ACH for all the thermal zones of the light weight and heavy weight houses was assumed.

The infiltration value (0.57 ACH) was assumed to be the same for the two simulations mainly for strict comparative purposes. In practice 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 building is exposed to wind. In this study a wind sensitivity of 0.1 ACH was assumed in all the thermal zones for both the light weight and heavy weight houses. It was assumed that surrounding buildings provide some sheltering as is the case on the CSIR test site.

3.3.5 Comfort band

The temperature comfort band for an air conditioned building used in this study is (20˚C - 24˚C) as recommended in SANS 204:201 (2011). For this study, this band was assumed for all the thermal zones. The zones are artificially assumed to be air conditioned for the software to be able to calculate heating and cooling loads. The acceptable range of humidity levels in buildings is between 30% - 60% for an energy efficient building SANS 204:201 (2011). For this study a design relative humidity of 60% was assigned to all the thermal zones. The design average air velocity must not be higher than 0.8 m/s (ANSI/ ASHRAE. 2004). For this study a design air velocity of 0.7 m/s was assumed for all the thermal zones to avoid un comfortable draughty conditions.

3.3.6 Occupancy

To compare the thermal performance of the two houses, operational schedules and occupancy were assumed to be identical. Both cases were assumed to be operating for 24 hours in order to assess the diurnal thermal performance. Zero occupancy was assumed in each case in order to simplify the analysis.

3.4 Detailed description of the high thermal mass and light weight (insulated) reference house

Table 2: Detailed description of the high thermal mass (**Case A**) and light weight (insulated) (**Case B**) reference houses

Element	Low mass (high insulation/ R-value house)	High thermal mass house
Roof	30 mm concrete tiles[1], 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	6.4 mm gypsum board. U_{value} = 5.58 W/m^2.K, Thermal lag = 0.06 hrs	6.4 mm gypsum board. U_{value} = 5.58 W/m^2.K, Thermal lag = 0.06 hrs
Floor	75 mm Concrete 1-4 dry, 10mm cement screed. U_{value} = 3.51 W/m^2.K, Thermal lag = 2.15 hrs	75 mm Concrete 1-4 dry, 10mm cement screed. U_{value} = 3.51 W/m^2.K, Thermal lag = 2.15 hrs

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

Table 3: Detailed description of high thermal mass and light weight (high R-value) alternative building envelope materials for energy evaluation. (The colour codes matches the bar graphs colours in Figures 6 and 7 below)

Case	Roof	External wall	Internal wall	Ceiling	Floor
C	Same as in Table 2	Same as in Table 2 under low mass (high R-value house)	Same as in Table 2 under low mass (high R-value house)	140mm glass wool insulation, 6.4 mm gypsum board. U_{value} = 0.26 W/m^2.K, Thermal lag = 0.44 hrs	Same as in Table 2
D	30 mm concrete tiles, 0.2 mm polyethylene (high density) and 40 mm isotherm insulation. U_{value} = 0.93 W/m^2.K, Thermal lag = 0.96 hrs	Same as in Table 2 under low mass (high R-value house)	Same as in Table 2 under low mass (high R-value house)	140mm glass wool insulation, 6.4 mm gypsum board. U_{value} = 0.26 W/m^2.K, Thermal lag = 0.44 hrs	Same as in Table 2
E	Same as in Table 2	15 mm plaster, 220 mm dense concrete and 15 mm plaster. U_{value} = 3.05 W/m^2.K, Thermal lag = 6.3 hrs	Same as in Table 2 under high thermal mass house	140mm glass wool insulation, 6.4 mm gypsum board. U_{value} = 0.26 W/m^2.K, Thermal lag = 0.44 hrs	Same as in Table 2
F	Same as in Table 2	15 mm cement plaster, 110 mm brick normal fire clay, 50 mm mineral wool insulation, 110 mm brick normal fire and 15 mm cement plaster. U_{value} = 0.59 W/m^2.K, Thermal lag = 9.08 hrs	Same as in Table 2 under high thermal mass house	140mm glass wool insulation, 6.4 mm gypsum board. U_{value} = 0.26 W/m^2.K, Thermal lag = 0.44 hrs	Same as in Table 2

Table 4: Continuation of Table 3

G	Same as in Table 2	15 mm cement plaster, 50 mm mineral wool insulation, 220 mm brick normal fire clay, 50 mm mineral wool insulation and 15 mm cement plaster. U_{value} = 0.33 $W/m^2.K$, Thermal lag = 10.16 hrs	Same as in Table 2 under high thermal mass house	140mm glass wool insulation, 6.4 mm gypsum board. U_{value} = 0.26 $W/m^2.K$, Thermal lag = 0.44 hrs	Same as in Table 2
H	Same as in Table 2	15 mm plaster, 220 mm dense concrete and 15 mm plaster. U_{value} = 3.05 $W/m^2.K$, Thermal lag = 6.3 hrs	Same as in Table 2 under high thermal mass house	Same as in Table 2	Same as in Table 2
I	Same as in Table 2	15 mm cement plaster, 110 mm brick normal fire clay, 50 mm mineral wool insulation, 110 mm brick normal fire and 15 mm cement plaster. U_{value} = 0.59 $W/m^2.K$, Thermal lag = 9.08 hrs	Same as in Table 2 under high thermal mass house	Same as in Table 2	Same as in Table 2

4 Results

Table 5 and 6 below show the annual heating and cooling loads for the six cities representing the Koppen Geiger climatic classifications shown in column one of said Tables.

Table 5: Annual cooling demand in six cities

K[2]	CASE	A	B	C	D	E	F	G	H	I
Cwa	Pretoria Cooling load (KWh)	6 046.91	4 439.42	525.13	478.87	798.92	471.09	590.87	5 813.95	5 186.31
BSk	Bloemfontein Cooling load (KWh)	4 995.50	3 771.85	280.88	250.87	593.55	341.90	411.86	4 797.00	4 335.69
Csb	Cape Town Cooling load (KWh)	1 117.51	991.46	69.85	61.30	80.73	36.61	61.77	1 035.62	900.22
Cfa	Durban Cooling load (KWh)	9 391.59	6 442.18	1 360.80	1 293.25	1 970.85	1 293.18	1 493.28	9 145.24	8 164.67
BWh	Musina Cooling load (KWh)	41 147.68	31 139.10	10 643.75	10 484.29	15 259.71	11 892.62	12 187.56	40 645.81	37 538.19
BSk	Kimberly Cooling load (KWh)	15 642.28	10 332.86	1 728.77	1 637.92	3 038.71	2 018.94	2 243.11	15 334.23	13 933.13

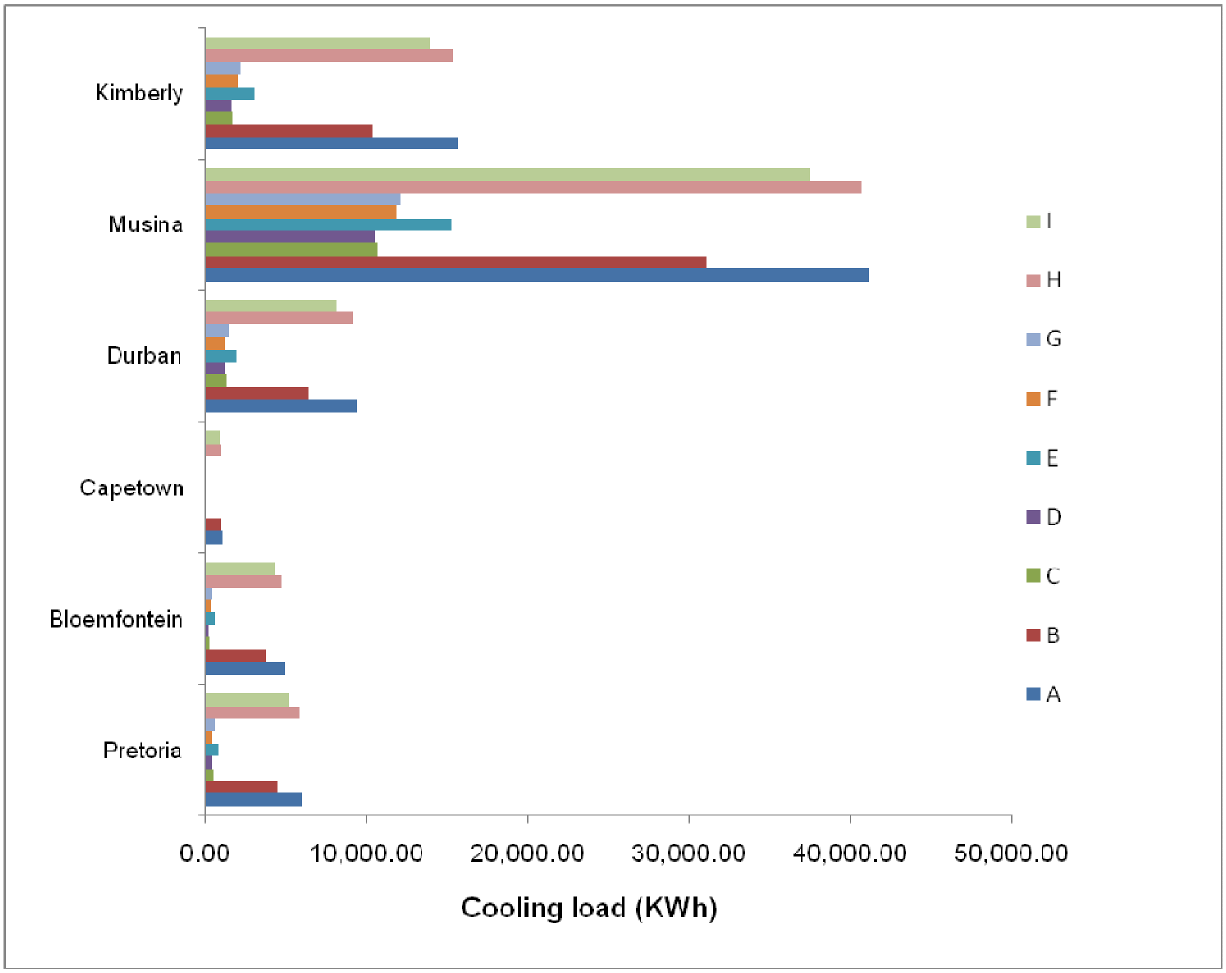

Figure 6: Annual space cooling demand in six cities

[2] K refers to Köppen-Geiger climatic map published in Green Building Handbook Volume 4, 2011, Chapter 12.

Table 6: Annual heating demand in six cities

K	CASE	A	B	C	D	E	F	G	H	I
Cwa	Pretoria heating load (KWh)	21 600.29	20 307.96	11 196.06	11 177.17	14 804.75	13 327.23	13 146.98	21 427.15	19 649.06
BSk	Bloemfontein heating load (KWh)	47 299.20	43 551.14	23 848.02	23 831.99	31 361.26	27 962.45	27 381.19	46 980.13	43 211.90
Csb	Cape Town heating load (KWh)	35 596.66	33 405.28	20 007.02	20 020.35	25 679.62	23 284.22	22 787.06	35 375.53	32 516.32
Cfa	Durban heating load (KWh)	6 832.69	6 408.08	3 336.42	3 318.52	4 774.33	4 145.06	4 126.92	6 761.17	6 087.11
BWh	Musina heating load (KWh)	2 328.40	2 102.31	921.17	906.54	1 774.83	1 379.41	1 379.73	2 293.03	1 887.30
BSk	Kimberly heating load (KWh)	25 118.54	22 559.33	10 823.55	10 812.93	15 328.35	13 260.13	12 937.77	24 943.25	22 614.46

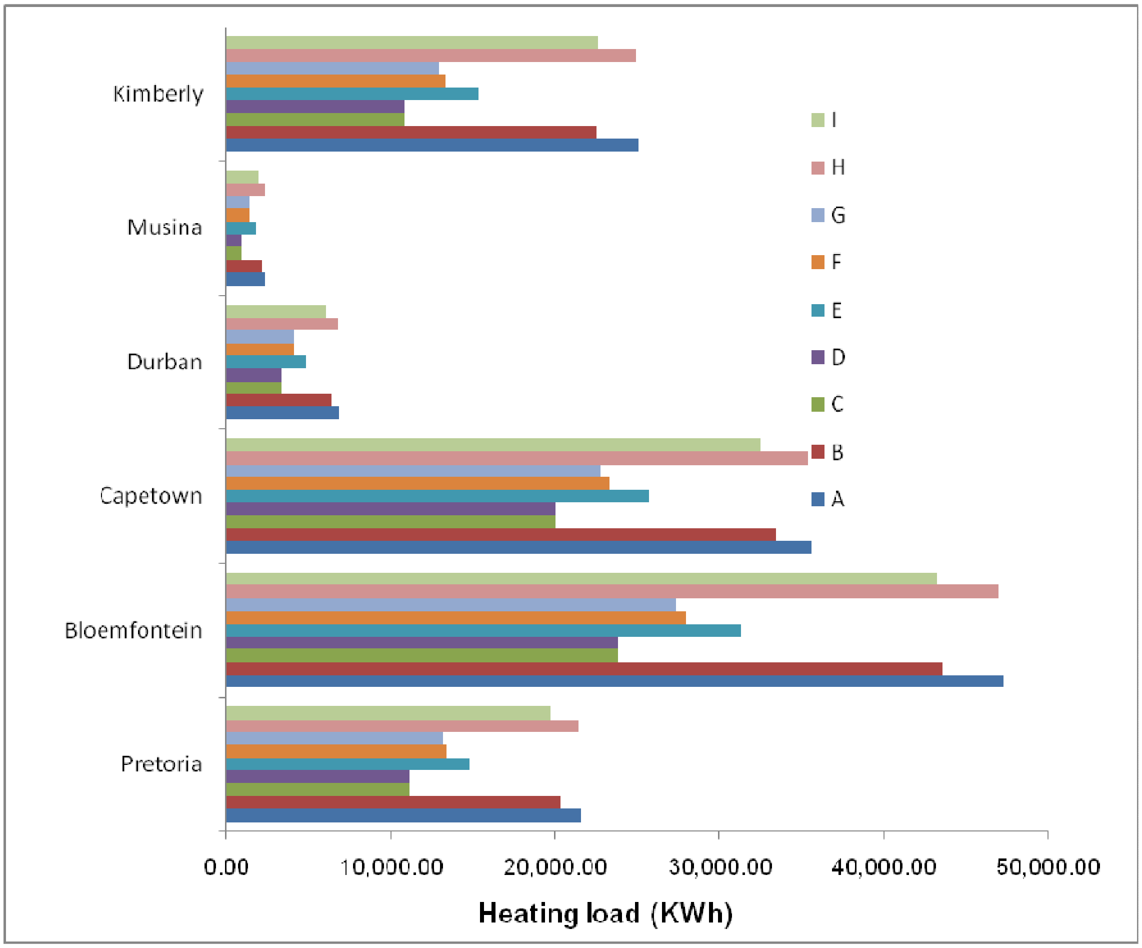

Figure 7: Annual space heating demand in six cities

5 Analysis of results

Figures 6 and 7 indicate that some cities require far much more space heating and space cooling than others. This correlates to the intensity of winter and summer months in these cities. Bloemfontein has the highest space heating energy requirements and Musina has the least space heating energy requirement. Cape Town has the least space cooling energy requirement and Musina has the highest space cooling energy requirement.

In cases C, D, E, F and G the lengths of the bar graphs for both heating (Figure 7, Table 6) and cooling (Figure 6, Table 5) are shorter in all six cities when compared to lengths of bar graphs for cases A, B, H and I (See Tables 2 , 3 and 4). The difference between cases C, D, E, F and G and A, B, H and I is that C, D, E, F and G has 140 mm glass wool on the 6.4 mm gypsum ceiling board whereas cases A, B, H and I has only 6.4 mm gypsum board as ceiling. This result indicate the importance of ceiling insulation. This is a passive intervention that is effective for both heating in winter and cooling in summer in all the six South African climatic regions investigated.

In cases C and D, the lengths of bar graphs for both heating and cooling are similar for both cases (C and D) in the six cities. The difference between construction C and D is that D has 40 mm isotherm roof insulation. The fact that the heating and cooling loads remain similar even after adding roof insulation on top of ceiling insulation indicates that adding roof insulation on top of an insulated ceiling does not change the heating and cooling loads in all the six cities.

The bar graphs for cases C and D are the shortest for both space heating and space cooling in all the six cities when compared to lengths of bar graphs for cases A, E, F, G, H and I. Cases C and D are constructed from high R_{value} and low thermal mass building envelope materials when compared to cases A, E, F, G, H and I. Therefore high R_{value} and low thermal mass building envelope materials are much more energy efficient when compared to low R_{value} and high thermal mass building envelope materials in the six cities.

6 Conclusions

When designing buildings in the six cities that represent a cross section of climatic conditions in South Africa, ceiling insulation (below the roof) is beneficial.

Given the materials stated in detail above, highly insulated walls and ceilings results in lowest heating and cooling requirements in all six cities.

This Chapter analysed heating and cooling requirements only. However there are other factors as well that are not addressed in this Chapter such as indoor temperature variation and thermal comfort. From simulations that are not shown in this Chapter, thermal mass has been shown to decrease temperature swings and light weight steel has high temperature variations.

As already discussed above, a highly insulated building saves space conditioning energy. For a high thermal mass building to match the insulating capacity of a highly insulated building, it requires quite a substantial structure. A combination of both insulation and thermal mass will be more beneficial (refer to cases F and G).

In another related simulation aimed at investigating different combinations of thermal mass and insulation. In this case 100 mm polystyrene insulative layer was put under the floor slab. Surprising result was that number of thermal discomfort hours (too hot hours) increased (Kumirai, et al. 2011, Willrath). From this it was concluded that the insulation under the floor increasingly isolates the room from the thermal mass of the ground.

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