A NOVEL ALGORITHM FOR DETERMINING THE ACTIVE THERMAL CAPACITY OF MASONRY WALLING IN THE SETTING OF ENERGY EFFICIENT BUILDING STANDARDS FOR SOUTH AFRICA

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SUMMARY

Developing the SANS 204:2010 standard for Energy Efficient Buildings in South Africa, requires research to define the "deemed to satisfy" thermal properties of external masonry walls. Using simplified CR Method equations, with comfort theory amplitude ratios, the required active thermal capacities of the building structure are calculated. A novel algorithm calculates the actual active thermal capacities of insulated masonry walls. Simulation models predict energy use and life cycle cost for building occupancy types, correlating well with the CR-value of a masonry wall. Minimum CR-values for masonry walls are proposed for inclusion in SANS 204:2010**.**

INTRODUCTION

Energy efficient building standards tend to focus on the thermal resistance requirements of the envelope, whilst the benefits of the thermal capacity present in masonry construction, are less highlighted. More than 90% of South African buildings are constructed of masonry units (Lewis 2009). This is partly due to the empirical evidence and occupant experience, over centuries, of the temperature amplitude moderating and thermal lag effects of external walling with thermal capacity (C-value). The South African climate is typified by high diurnal temperature variance, with some climatic zones experiencing high absolute summer and / or low winter temperatures (Holm & Engelbrecht 2005). Therefore, under certain climatic conditions, the thermal capacity and resistance (R-value) inherent in the external masonry wall is insufficient in dealing with the difference (δT) between the average outdoor low temperature and the desired indoor comfort temperature. In such cases the R-value of the masonry is supplemented by insulation material, where the insulation value and the position of it relative to the C-value of the masonry, is a critical consideration. Much of the thermal capacity is rendered ineffective if highly insulating layers are placed inappropriately. The imperative to construct sustainable buildings leads to the development of the standard SANS 204:2010 Energy Efficient Buildings in South Africa. This requires research into determining a scientific and practical basis for specifying deemed-to-satisfy (DTS) thermal properties for external walling.

RESEARCH METHODOLOGY

The research process commences with a review and simplification of the CR Method equations, which when combined with equations from adaptive thermal comfort theory, allows for calculation of the required active thermal capacity of the various elements of the building envelope. An algorithm for calculating active thermal capacity is developed and applied, providing the basis for a comparison of actual wall system values with the requirements derived from the CR Method. Simulation models predict energy consumption and life cycle costs, providing the basis for correlations with the thermal properties of external masonry walls. Consideration of the simulation model results and the construction methods available in South Africa leads to the definition of minimum DTS levels for SANS 204:2010. Figure 1 below provides a flowchart of the primary research activities.

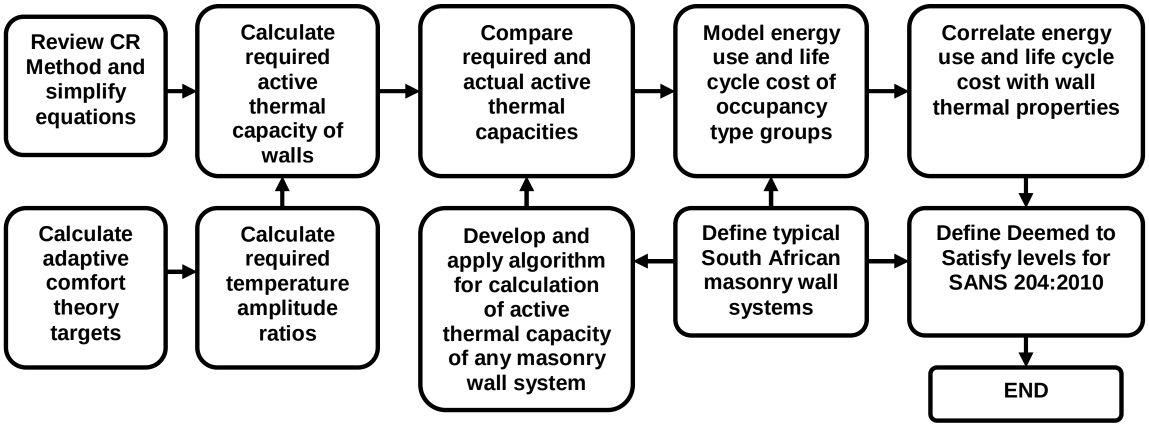


Figure 1. Flowchart of research methodology

CR METHOD SIMPLIFICATION

The National Building Research Institute of the Council for Scientific and Industrial Research derived the CR Method (Wentzel et al 1981) by correlating many field measurements of typical South African constructions with a theoretical model. The CR Method states that the product of the active thermal capacity (C_{act}) of the building structure and the equivalent exposed envelope resistance (R), is experimentally correlated to the temperature amplitude ratio, α_i/α_o, where α_i is the desired interior temperature amplitude and α_o is the actual outdoor temperature amplitude of the specific location. This is presented in equation (1).

$$\alpha_i/\alpha_o = (48.9 \text{ x } R)/(\sum C_{act} \text{ x } R)^{0.903} \tag{1}$$

As “R” appears with similar weight both in the numerator and denominator of equation (1), a simplification of the equation is possible, including empirically derived constants. This is shown as equations (2) and (3), for typical winter and summer conditions, as developed by Matthews (1986).

$$\alpha_{iw}/\alpha_{ow} = 260.17/C_{actw} \tag{2}$$

where,

α_{iw} = desired indoor temperature amplitude in winter
α_{ow} = actual outdoor temperature amplitude in winter
C_{actw} = desired active thermal capacity in winter

$$\alpha_{is}/\alpha_{o\ sol\text{-}air} = 150.41/C_{acts} \tag{3}$$

where,

α_{is} = desired indoor temperature amplitude in summer
$\alpha_{o\ sol\text{-}air}$ = actual solair outdoor temperature amplitude in summer
C_{acts} = desired active thermal capacity in summer

The active thermal capacity (C_{act}) of a building structure is calculated by considering any insulation relative to the thermal mass of each structural element, as the position and R-value of all elements determine the net C-value available for heat exchange. Both C and C_{act} are expressed in kJ/K of the envelope area, thereby quantifying the amount of heat energy required to raise the temperature of the envelope by 1K. The C and C_{act} values can also be expressed in terms of the volume of indoor air encompassed by the shell, or in terms of the net external wall area.

ADAPTIVE THERMAL COMFORT

Arguably, the main driver of energy consumption in buildings in general, is the lack of indoor thermal comfort. This, in turn, is influenced by the climatic conditions, the timing and duration of occupancy, the occupation density, occupant activities, other comfort demands, the type of ventilation, and the building design and size. Using equations (4) and (5), from De Dear et al (1997) and Auliciems and Szokolay (2007), the adaptive thermal neutrality temperatures, T_n, and permissible temperature ranges for all South African climatic regions are established for air-conditioned and naturally ventilated buildings at an 80% and 90% acceptability level.

Naturally ventilated: $T_n = 18.9+0.255 \times ET_{outd} \pm 2.5K\ (90\%) \text{ or } \pm 3.5K\ (80\%)$ (4)

Air-conditioned: $T_n = 21.5+0.11 \times ET_{outd} \pm 1.2K\ (90\%) \text{ or } \pm 2K\ (80\%)$ (5)

where, ET_{outd} is the new Effective Temperature outdoors for the specific location.

T_n values for 14 locations, spanning all 6 climatic zones in South Africa are illustrated in Figure 2 for naturally ventilated buildings.

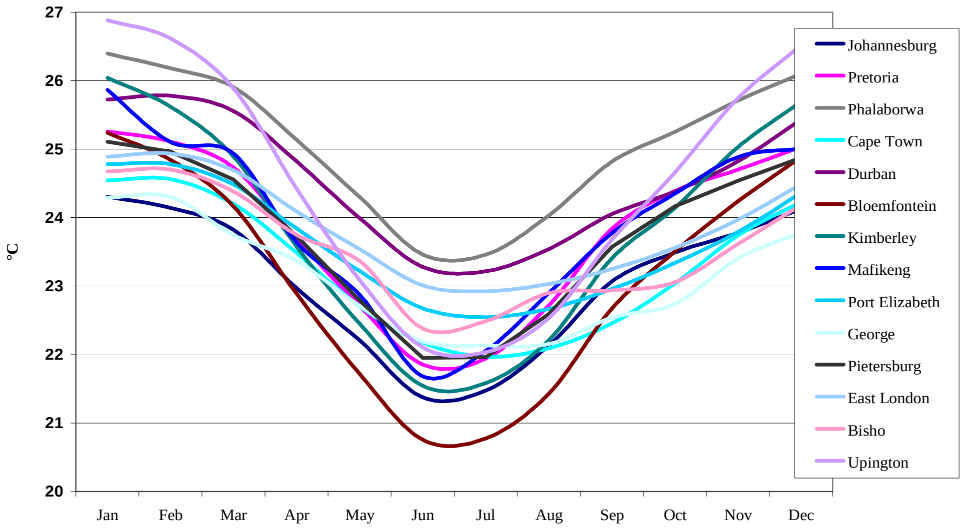


Figure 2. T_n values for naturally ventilated buildings

Since the desired indoor temperature amplitude (α_i) is known from equations (4) or (5), and the monthly average outdoor amplitude (α_o) is known from weather data for a specific location, the temperature amplitude ratio (α_i/α_o) is readily established. Figure 3 illustrates the desired ratios for air-conditioned buildings at 80% acceptability to occupants.

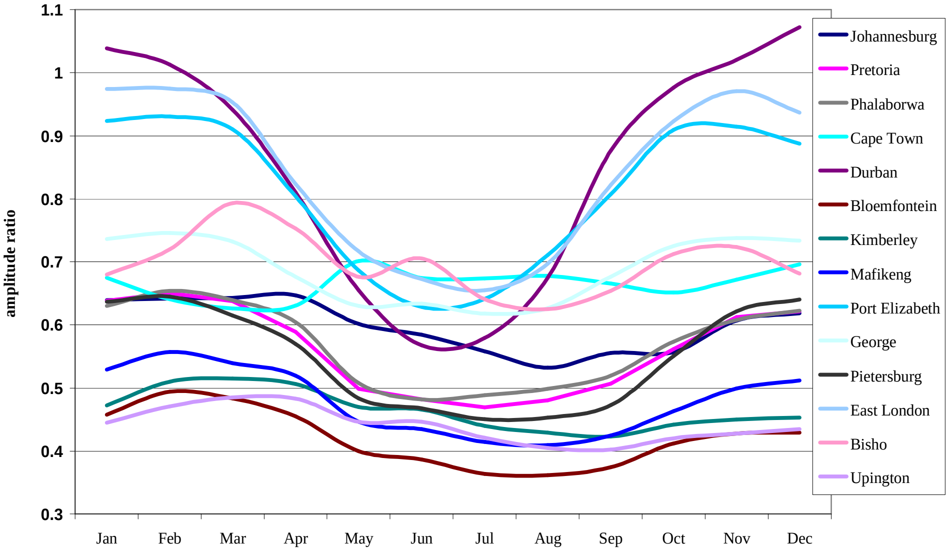


Figure 3. Desired amplitude ratio for 80% acceptability in air-conditioned buildings

REQUIRED C_{act}

Using equations (2) and (3) and the desired amplitude ratio, the minimum required C_{act} is calculated. The values for winter of the net external wall area of a building that is naturally ventilated are shown in Figure 4 for 9 locations. It is important to note that these values represent the minimum thermal performance levels required if the external walls are the only elements (excluding the roof) of the building structure capable of achieving the required amplitude ratio, with no artificial heating or cooling system contribution. The floors and internal walls are not considered in energy efficient building regulations, as occupants will generally cover these surfaces in a variety of ways.

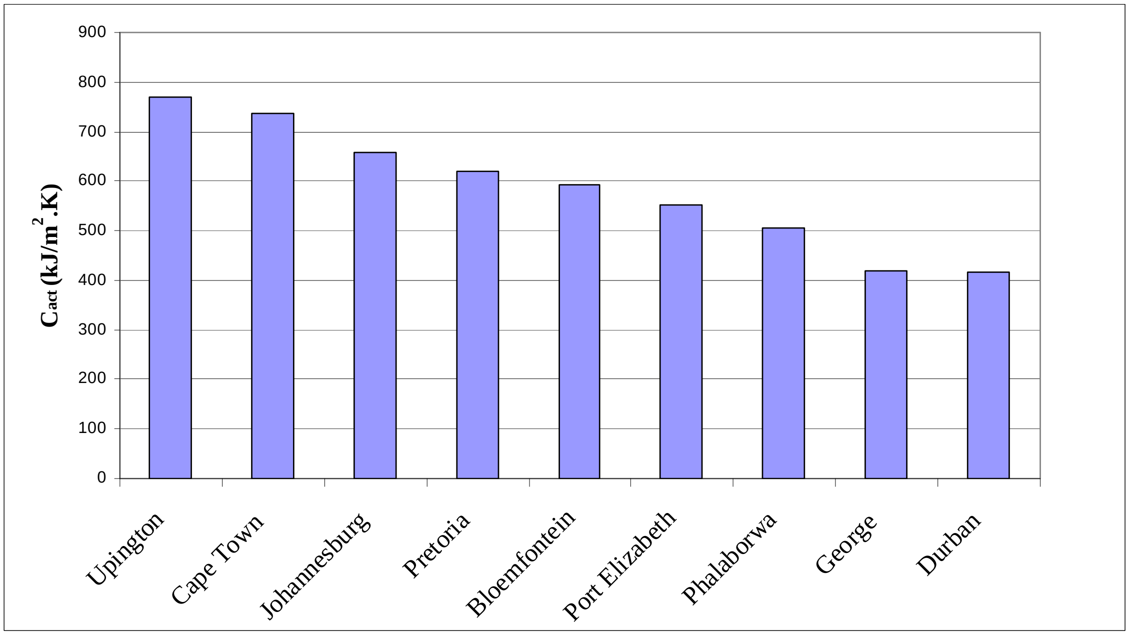


Figure 4. C_{act} for the net external wall area of a naturally ventilated building in winter

ALGORITHM FOR DETERMINING THE ACTIVE THERMAL CAPACITY

The original CR Method applies thermal resistance weighting factors to the net thermal capacity available in the external and interior walls, floors and ceilings of a building in order to reflect the ease with which the thermal capacity can interact with the indoor air. Using the algorithm in the original CR Method for external walls, it is possible for the active thermal capacity value to exceed the net thermal capacity of the wall. In order to address this deficiency, a novel algorithm is developed. Following a similar argument to Wentzel et al (1981), the net thermal capacity is multiplied by a thermal resistance weighting factor, ε, to calculate the thermal capacity that can actively partake in heat exchange with the indoor air. However, ε, is now defined so as to ensure that it cannot be larger than unity, whilst reflecting the relative active contribution of the thermal capacity.

For illustration of the algorithm consider a typical external masonry wall system as shown in Figure 5. Let there be a masonry wall construction with a total masonry width of m, excluding a layer of insulating material of thickness t_i. Let the distance from the outer surface of the masonry to the outer surface of the insulating layer be x .

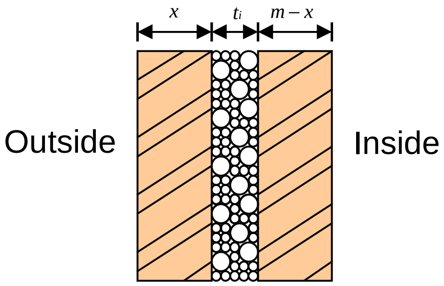


Figure 5. Illustrative masonry wall system

Equations (6), (7) and (8) and the values in Table 1 are used to calculate the thermal capacity (C) of each masonry layer, and the total masonry section, for a typical homogenous fired clay brick wall system, without consideration of the effect of an insulation layer on the heat exchange with the indoor air.

$$C_{x} = x \text{ x } \rho \text{ x } C_{p,} \text{ in kJ/m}^2\text{.K} \tag{6}$$

$$C_{m-x} = (m - x) \text{ x } \rho \text{ x } C_p, \text{ in kJ/m}^2\text{.K} \tag{7}$$

$$C_{tot} = C_{x} + C_{m-x} = m \text{ x } \rho \text{ x } C_p \tag{8}$$

$$= 400 \text{ kJ/m}^2\text{.K}$$

Using the algorithm and the standard surface film co-efficients for a masonry wall, the thermal resistance weighting factors, ε, are calculated for each masonry layer according to equations (9) and (10) and the values in Table 1. The centre of gravity (assumed to be the midpoint) of each masonry layer is used for determining the relative contribution of its thermal resistance to the total thermal resistance of the wall system.

$$\varepsilon_{x} = (1/h_o + 0.5x/k_w)/(1/h_o + m/k_w + t_i/k_i + 1/h_i)$$

$$= (1/h_o + 0{,}5x/k_w)/R_{tot} \tag{9}$$

$$\varepsilon_{m-x} = ((1/h_o + x/k_w + t_i/k_i + 0.5(m - x)/k_w))/R_{tot}$$

$$= ((1/h_o + (0.5x + 0.115)/k_w + t_i/k_i))/R_{tot} \tag{10}$$

Table 1. Properties of wall system materials

Variable	Symbol	S.I.Units	Value
Total thickness of clay masonry	m	m	0.23
Thickness of clay masonry leaf	x , $m - x$	m	x , 0.23- x
Density of clay masonry	ρ	kg/m^3	2022
Specific heat capacity of clay masonry	C_p	kJ/kg.K	0.86
Outside surface co-efficient	h_o	W/m^2.K	20.00
Inside surface co-efficient	h_i	W/m^2.K	9.40

Thermal conductivity of clay masonry	k_w	W/m.K	1.00
Thickness of insulation	t_i	m	0.02
Thermal conductivity of insulation	k_i	W/m.K	0.04
Total thermal resistance of the wall system	R_{tot}	m^2.K/W	0.8864

The active thermal capacity (C_{act}) of each masonry layer is calculated by multiplying equation (6) with (9), and (7) with (10), respectively. This gives equations (11) and (12). The total active thermal capacity ($C_{act\ tot}$) is represented by equation (13), the sum of equation (11) and (12).

$$C_{act\ x} = C_x \text{ x } \varepsilon_x = 981x^2 + 98x\text{, in kJ/m}^2\text{.K} \qquad (11)$$

$$C_{act\ m-x} = C_{m-x} \text{ x } \varepsilon_{m-x} = -981x^2 - 1079x + 300\text{, in kJ/m}^2\text{.K} \qquad (12)$$

$$C_{act\ tot} = -981x + 300\text{, in kJ/m}^2\text{.K} \qquad (13)$$

The results of solving equations (11), (12) and (13) for x values from 0m to m = 0.23m is shown in Figure 6.

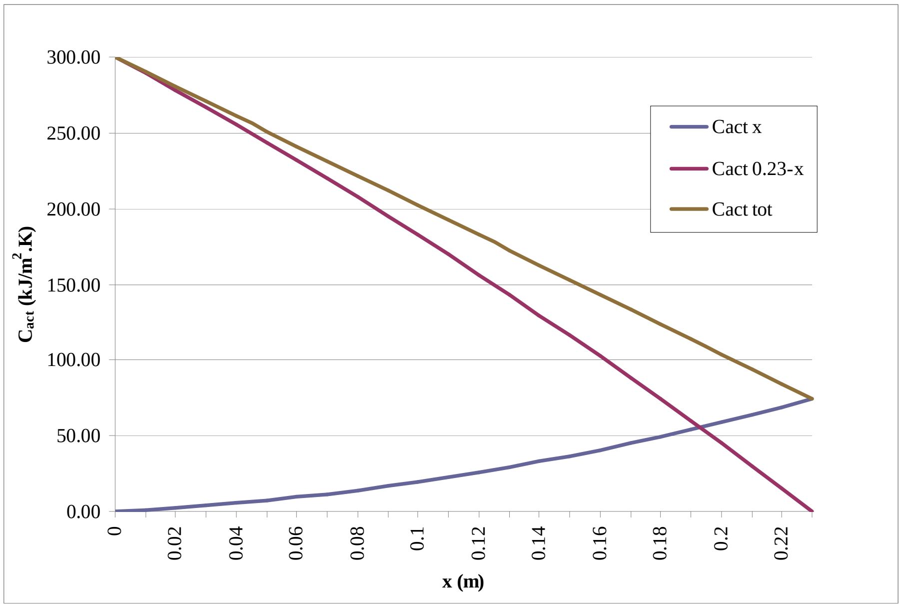


Figure 6. Active thermal capacity of the masonry wall system

The following observations are made from this illustrative case :

- $C_{act\ tot}$ reaches a maximum of 300 kJ/m²K when x = 0m, that is when the thermal insulation (R) is on the external face of the wall system.
- C_{tot} is 400 kJ/m^2.K, therefore 25% is not thermally interactive with respect to the indoor air.
- $C_{act\ tot}$ reaches a minimum of 75 kJ/m²K (18,75% of C_{tot}) when the thermal insulation is on the inside face of the wall system.
- If the thermal insulation is sandwiched in the middle between two equal 0.115m wide masonry layers, then the outer layer contributes 24,3 kJ/m²K while the inner layer

contributes 163 kJ/m²K (almost seven times more), producing a total of 187,3 kJ/m²K, which is 62,4% of $C_{act\ tot}$.

Oxtoby et al (2010) applies the algorithm to 31 types of actual masonry walling in South Africa, yielding $C_{act\ tot}$ values ranging from 103 to 170 kJ/ m²K.

ENERGY EFFICIENT BUILDING STANDARDS

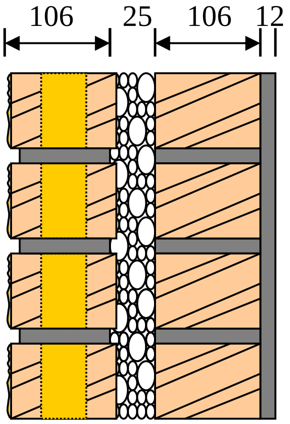
Holm et al (2010) apply the simplified CR Method to 31 building occupancy types, using the algorithm to calculate the thermal properties of 5 South African masonry wall systems. They simulate the energy consumption of 3 simplified building designs by means of thermal modelling and calculate the life cycle cost of achieving the desired average annual temperature amplitude, in 6 climatic zones. Considering the requirement for external walling to have appropriate combinations of thermal capacity and resistance, the inverse correlation between predicted energy consumption and the product of C and R is determined. The co-efficient of determination (R^2) is found to be 0.86 on average. In order to provide a practical and relatively straightforward way of specifying the minimum requirements for DTS compliance in energy efficient building standards, the product of C and R, namely the CR-value, is used. Equation (14) describes the calculation of the CR-value, which is the "time constant" property of the masonry wall system in units of time.

$$\text{CR-value} = C_{tot} \times R_{tot} \qquad (14)$$

Where, $C_{tot} = \sum C_n = C_1 + C_2 + C_3 + \ldots + C_n$, and $R_{tot} = \sum R_n = R_1 + R_2 + R_3 + \ldots + R_n$, with *n* distinct layers in the wall system. Figure 7 illustrates the cross section of a typical South African clay face brick masonry wall, with insulation to SANS204:2010 levels for a residence in Johannesburg. Equation (15) depicts the solving of equation (14) with the values for this wall system.

$$\text{CR-value} = 319\ \text{kJ/m}^2\text{K} \times 1.14\ \text{m}^2\text{K/W} \times (1000/3600) = 101\ \text{hours} \qquad (15)$$

106mm clay face brick (30% core), insulation 25mm glass wool (no air gap), 106mm clay plaster brick (no cores), 12 mm plaster, paint.



$C_{tot} = 319$ kJ/m^2.K
$R_{tot} = 1.14$ m^2.K/W
CR = 101 hours
$C_{act} = 162$ kJ/m^2.K

Figure 7. Face brick wall system illustrating CR-value

The minimum CR-values for compliance to SANS 204:2010 : Energy Efficient Buildings are listed in Table 2.

Table 2. Minimum CR-values in hours for external walls in SANS 204:2010

Minimum CR-values (hrs)	Climatic Zone					
Occupancy Type Group	1	2	3	4	5	6
Residential	100	80	80	100	60	90
Office & Institutional	80	80	100	100	80	80
Retail	80	80	120	80	60	100

Oxtoby et al (2010) simulates the energy consumption and calculates the life cycle cost of achieving the desired monthly temperature amplitude ratio in 6 climatic zones for a 130m^2 residence, by modelling the impact of 31 types of actual masonry walling on indoor conditions. An inverse correlation between predicted annual energy consumption and CR-value produces an average co-efficient of determination (R^2) of 0.8 for the power function. This further substantiates the efficacy of specifying minimum CR-values in SANS 204:2010, whilst further research is conducted into the most suitable methods for insulating masonry walls in climates, and for occupancy types, where this is required.

CONCLUSION

This research concludes that in high diurnal variance climates, as in South Africa, the external walls of buildings require not only thermal insulation in many instances, but also sufficient quantities of thermal capacity for energy efficiency. The CR Method demonstrates that small amplitude ratios require high C_{act} values, which temper the indoor climate to within the required comfort range. This reduces artificial heating and cooling energy, of great importance for buildings with large glazed areas, as they can overheat under the intense South African sun, and overcool during cold winter nights. The novel algorithm shows that the placement position and R-value of insulation in South African masonry walls is an important decision, as both affect the amount of thermal capacity actively available for heat exchange with the indoor environment. It shows that placing insulation layers on the inside of a masonry wall should be discouraged. Doing so would also increase the risk of condensation inside the external wall resulting in the loss of insulating value and increasing the risk of frost damage. Whilst the algorithm predicts that the thermal capacity is most active when insulation is placed on the outside, numerous other factors should be considered when deciding on the most sustainable option for that part of the walling envelope that interfaces directly with the environment. These would be factors such as life cycle cost, aesthetics, durability, fire resistance, acoustic properties, availability of wall systems, construction skills and so on. If insulation is placed in the middle of two homogenous masonry layers, then the active thermal capacity of the interior leaf is seven times as effective as that of the outside leaf. Placing lighter masonry on the exterior and heavy masonry on the interior face therefore makes sense, as is typically found in South African face brick and plaster brick combination walling systems.

FURTHER RESEARCH

Understanding of the heat transfer equations in modelling software will be useful for determining the suitability of the novel algorithm as a means of specifying minimum levels of C_{act} for external masonry walling in South Africa. Such investigation would include a parametric study to determine the response of the simulation model to varying positions and levels of insulation in masonry walls.

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