The role of thermal mass in energy efficiency for office buildings under different climatic regions of South Africa: Optimising the dual role of concrete for structure and thermal mass.

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Declaration

I declare that this research report is my own work. It is being submitted for the degree of Master of Architecture in Sustainable and Energy Efficient Cities to the University of Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination at any other University.

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Abstract

As a passive design intervention, material selection of thermal mass and its effects on thermal performance of buildings should be assessed as part of the energy performance strategy for buildings. This study highlights the influence of heavyweight versus lightweight concrete as thermal mass on indoor thermal comfort of office buildings in two different climatic regions of South Africa.

The study focuses on two case study office buildings, one in Johannesburg and the other one in Durban. Energy performance of the buildings was based on a quantitative research approach, whereby the heating and cooling energy loads were simulated for both baseline heavyweight concrete versus lightweight concrete as thermal mass interventions. Simulation was based on the Integrated Environmental Solutions Virtual Environment (IES_VE) software and involved building modelling parameters such as building envelope composition and properties, solar radiation, climatic factors, internal gains and natural air flow.

The study finds that lightweight concrete construction was only favourable for annual heating energy loads required for thermal comfort, with an energy savings of 12.71MWh per annum and 4.58MWh per annum for the Johannesburg and Durban case study buildings respectively. In contrast, baseline heavyweight concrete construction was deemed favourable for cooling energy loads required to achieve thermal comfort. The difference in annual cooling energy loads performance between heavyweight and lightweight concrete amounted to 21.32MWh and 22.85MWh for Johannesburg and Durban respectively. Since cooling energy loads accounted for 85% of overall simulated energy loads in Johannesburg and 96% of overall energy loads in Durban, heavyweight concrete was deemed favourable for both buildings and hence for their respective climatic regions. In contrast, lightweight concrete as thermal mass was found to be neither technically viable nor economically feasible as thermal mass for building energy efficiency for both climatic regions. Its additional energy costs were derived to be R11 340.00 for the building in Johannesburg and R23 020.20 for the building in Durban when compared to heavyweight concrete construction. Furthermore upfront cost of construction with lightweight concrete would be greater than the cost for heavyweight concrete in South Africa, thus resulting in greater losses, which further weakens the viability case for lightweight concrete.

Key words: Thermal mass, passive design, energy performance simulation, heating and cooling energy loads.

Dedication

I dedicate this degree to the significant people in my life that have and continue to influence, inspire and encourage me to fulfil my goals.

Firstly, I would like to thank my parents for their unwavering support and love and for taking time to care for me through stressful and difficult situations. To my sister, for her constant belief in my capabilities, and her positive influence in my life. Ma, Baps and Sads, you have been the driving force behind my successes and I am nothing but grateful.

Lastly, to my partner, friends and family for keeping me sane through testing times and reminding me that I am strong, capable and have the drive within me to complete the goals I set out for myself.

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Thanks to my fellow M(Arch)SEEC classmates for constantly reminding me of my passion within the sustainable built environment. It is inspiring to be amongst like-minded people and my hope is that we can all contribute to the advancement in sustainability within the built environment and beyond.

This degree has been a challenging, yet rewarding experience. It has been everything but easy to manage a work-life balance. However, I am grateful that I have support from family, friends and colleagues.

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List of abbreviations and acronyms

ACI	American Concrete Institute
ASHRAE	American Society of Heating, Refrigerating and air-conditioning engineers
ASL	Above sea level
DOE	Department of Energy
EE	Energy efficiency
EP	Energy Plus
EPW	Energy Plus weather
EUI	Energy use intensity
HVAC	Heating ventilation and air conditioning
HWC	Heavyweight concrete
IES_VE	Integrated Environmental Solutions _Virtual Environment
ILWC	Infra-lightweight concrete
IWEC	International weather for energy calculations
kWh	Kilowatt hour
LWC	Lightweight concrete
MPa	Megapascals
MWh	Megawatt hour
NRMCA	National ready mix concrete association
NWC	Normal weight concrete
SANS	South African National Standards
SBCI	Sustainable building and climate initiative
UNEP	United Nations Environmental Program

Chapter 1: Background and motivation for the study.

1.1 Overview

This chapter reviews the background of the study and necessitates further investigation on the extent to which thermal mass selection can contribute towards passive energy efficient interventions for buildings. The research objectives are outlined, leading to the main research question and sub-questions which guide the study.

1.2 Introduction

Buildings are responsible for more than 40% of global energy use (UNEP_SBCI, 2009). Recent findings also show that the largest usage of energy in typical commercial office buildings is due to Heating Ventilation and Air Conditioning (HVAC) systems. According to HVAC HESS (2013), HVAC systems in offices consume approximately 39% of total building energy. The trend of fully controlled indoor climates for buildings through mechanical systems is thus contributing to a significant increase in energy demand (Edenhofer *et al*., 2014). Due to high levels of energy consumption for heating and cooling within buildings, ongoing investigation into the interactions between a building's design, material selection and passive energy efficiency interventions remains crucial.

In recent years, energy efficiency measures are being incorporated more frequently during the design phase of buildings. In South Africa, national building standards for energy efficiency, such as mandatory SANS 10400-XA:2011 and voluntary SANS 204:2011 demonstrate a growing interest towards reducing the overall energy consumption within new buildings. Thermal mass can have significant influence on the thermal comfort of occupants as well as related energy consumption in buildings; however these building standards offer little explanation and no guidance on use of thermal mass. With building envelope efficiency in mind, SANS 10400-XA:2011 and SANS 204:2011 highlight the requirements for compliance with maximum annual energy consumption per building classification. Even though focus on the thermal resistance (R-values) and thermal transmittance (U-values) of composite building elements are taken into consideration, these values, as stipulated for the various climatic zones, provide a guide for compliance, rather than for energy optimisation.(SANS 10400-XA, 2011) and (SANS 204, 2011)

In line with these expectations, the effects of thermal mass as a passive energy efficiency intervention were investigated further. In addition, later versions of the SANS 10400-XA and SANS 204 can be fine-tuned to better align with the effects of thermal mass as experienced under different climatic zones.

1.3 Background

The study focused on the influence of thermal mass on moderating energy loads for heating and cooling within buildings under different climatic zones of South Africa. Thermal mass is defined as a material's resistance to change in temperature and its ability to absorb and store heat energy (Karlsson, 2012). Thermal mass depends on density and specific heat capacity of a material and it measures the heat storage capacity of an element (Arcuri *et al.*, 2016). Characteristically, high density thermal mass materials such as concrete and brickwork have a greater ability to increase the thermal storage capacity of a building's envelope and structure. However, it will also take longer for such materials to release the stored heat (*ibid*). In contrast, lightweight materials such as steel and timber allow for faster thermal exchange. Thermal mass materials of a building would in turn have an influence over the indoor air temperature, occupant comfort levels and overall air-conditioning requirements. Therefore, thermal mass can be optimised towards passive solar heating and cooling design within buildings. However, it should be noted that thermal mass is not required to the same level across different climatic zones. Due to varying climatic conditions, it cannot be assumed that buildings with high thermal mass would reduce the overall energy consumed in a building as compared to low thermal mass (Baggs, 2013).

Factoring in thermal mass to optimise the passive design of buildings has many benefits. High density thermal mass materials (characterised by a high heat capacity) such as concrete, brickwork, and rock have a greater ability to absorb, store and slowly dissipate heat energy from solar radiation or other load sources into a building. This may reduce the energy input required to respond to daily maximum and minimum temperature differentials as thermal mass moderates indoor temperature fluctuations. Consequently, lower energy requirements lead to reduced ecological impacts. Furthermore, high density thermal mass materials allow for a greater time lag in the flow of heat energy in summer from the exterior to the interior. This lag effect is beneficial in commercial and residential buildings under climates experiencing very hot mid-day temperatures and lower night temperatures. (Portland Cement Association, 2018).

Thermal mass can also shift energy demands from peak to off-peak time periods ultimately reducing operational costs while simultaneously minimising air conditioning needs for indoor thermal comfort (Arcuri *et al.*, 2016). Thermal mass can also be used optimally through strategic placing of walls and to cool a space through the use of shading devices that shield thermal mass from direct solar gain. Introducing a cross breeze into a building can also remove unwanted heat stored in exposed high thermal mass materials. (Portland Cement Association, 2018).

Materials with high thermal mass (heavier and denser materials) may take longer to release the stored heat once the heat source is removed. In such cases, a less dense material might be more favourable (Arcuri *et al*, 2016). Areas with stable temperature regimes (no major difference between minimum and maximum daily temperatures) respond negatively to high thermal mass materials. In areas that constantly experience high temperatures, a high thermal mass material would absorb external heat and slowly dissipate this heat energy into the building thereby adding more heat to a space. Similarly, in areas that constantly experience low temperatures, materials with high thermal mass would absorb the heat required to warm the building interior.

1.4 Problem statement

Given its versatility, durability and high compressive strength, concrete is one of the main construction materials used in the building industry worldwide. In addition to its structural properties, normal weight concrete has a high thermal mass. This means that normal weight concrete, which is characterised by a high heat capacity, can absorb and retain heat energy for long periods of time and therefore has the potential to reduce the total energy consumption within a building. Normal weight concrete is known to be most appropriate in climates with a large diurnal temperature range. The thermal mass effect is an important property of concrete that is often disregarded by structural engineers, architects and green building consultants during the initial design phase of buildings, even for green rated buildings. “Understanding of thermal mass impact on building energy consumption and demand at the earliest design stage can be very helpful in the design of high performance buildings.” (Andelkovic *et al.*, 2012:508). Depending on the climatic zone under investigation, thermal mass would have varying impacts on thermal comfort and related energy consumption. Optimisation of the type and placement of construction materials such as concrete (from choices amongst wet materials) can lead to reduced building energy demand in heating and cooling processes for thermal comfort. Moreover, the opportunity for lightweight concrete construction with a lower embodied energy and thermal mass capacity (compared to normal/heavy weight concrete) should be explored further towards optimising energy efficiency in buildings, especially in climatic regions with more stable diurnal temperatures.

1.5 Rationale of the study

This study aids in understanding building sensitivity to changes in temperature cycles occurring under various climatic zones and the manner in which this directly influences energy demand in relation to thermal comfort. Furthermore, if thermal mass considerations are implemented appropriately into building design and construction, it has the ability to induce a comfortable indoor thermal environment, without the overdependence on energy intensive HVAC systems. This has the potential for reducing energy consumption, thus reducing greenhouse gas emissions and the negative impact on climate.

1.6 Objectives

The study aims at understanding the influence of heavyweight and lightweight concrete thermal mass material on indoor thermal comfort of office buildings under different climatic regions in South Africa. The findings of the study would therefore guide professionals one step closer towards designing energy efficient buildings based on better insight on the extent to which thermal mass selection could contribute towards reducing heating and cooling energy loads, especially for office buildings. In addition, the study aids in understanding which concrete type (heavyweight or lightweight), is more suitable for energy efficiency in building envelopes located in different climatic regions. This analysis is based on the assumption that the structural integrity/performance of the building is kept intact when considering lightweight and heavyweight concrete options with similar strengths. By extension, the life cycle cost implications of heavyweight and lightweight concrete construction in reducing building energy loads was assessed.

1.7 Research question and sub-questions

The study was therefore guided by the following research question and sub-questions:

1.7.1 Main research question

How can the dual role of concrete elements as structural systems and thermal mass be adapted and optimised towards energy efficiency through passive cooling and heating for office buildings under different climatic regions of South Africa?

1.7.2 Sub-questions

- How do daily and seasonal temperature cycles influence thermal comfort within buildings and which passive energy interventions can be utilised for optimising thermal comfort, under different climatic zones of South Africa?

- Given structural performance priorities, what would be the responsive thermal mass variations for concrete in line with thermal comfort needs and temperature cycles for various climatic zones of South Africa?

- What would be the overall optimal heating and cooling energy loads for building energy efficiency from thermal mass variations (lightweight concrete versus normal/heavyweight concrete) in different climatic zones of South Africa?

- What would be the technical viability and economic feasibility of thermal mass variations in comparison to the energy savings arising from the energy efficiency gains across the various climatic zones?

1.8 Expected findings (working hypothesis)

Based on experience with the high thermal storage capacity of commonly used heavyweight concrete as the baseline, the study expected to find that heavyweight (high density) concrete would be favourable in colder climate regions as characterised by a significant difference in daily maximum and minimum temperatures, while lightweight concrete would be preferable in a climate region that experiences a more steady temperature regime. Exploratory appraisal on the climatic conditions of major cities in South Africa would suggest that, buildings in Johannesburg require moderate density thermal mass materials in order to minimise over heating in summer and over cooling in winter. In contrast to Johannesburg's cold interior climate, a city such as Durban with a warm, humid and steady temperature regime would benefit from lightweight, low thermal mass material.

By considering thermal mass in building design, it is expected to yield significant savings from related energy efficiency performance (through the reduction of heating and cooling energy loads usually supplemented by HVAC systems). This would subsequently reduce the overall energy use intensity (EUI) within buildings and its related carbon footprint.

1.9 Limitations and delimitation of the study

The study primarily investigated passive thermal control through thermal energy storage, and therefore focused on how thermal properties of concrete elements influence energy consumption and thermal comfort within buildings subject to different climatic regions. Given that there are many influencing factors that affect the performance of thermal mass of a building, it was considered necessary to set this investigation within a case study context for analysis and comparison purposes. Key findings for this study are derived from primary and secondary data sources, both of which certain assumptions were made that can have significant implications when adapting the results to other contexts. As a result, generalising these results would be subject to the limitations discussed below.

Firstly, the study only focuses on concrete as a thermal mass and the extent to which it contributes towards energy efficiency of buildings, where existing buildings were used as case studies. However, this does not imply that retrofitting these existing buildings with the structural concrete studied was envisaged as a realistic intervention. This investigation of thermal mass as a passive energy efficient intervention is for comparative purposes only between existing and new construction. In addition, concrete has many complexities and its properties can be altered through various design mixes. Over many decades, there have been advances in concrete design through the addition of cement replacements and additives, the use of different sized aggregates as well as varying proportions of water, aggregate and cement thus influencing the overall density of concrete. For the purposes of this study, energy performance using two concrete types; heavyweight and lightweight concrete were compared as described in more detail in Chapter 5.

Secondly, the influencing factors that affect the performance of thermal mass of a building such as internal gains, orientation of the building, shading, the area and positioning of fenestrations, natural ventilation and air exchanges as well as occupancy and occupancy patterns are unique for every building. This suggests that any findings emerging from the proposed study cannot be generalised without considering the unique factors in each building.

One of the main influencing factors that affect the thermal performance outcomes of thermal mass is the climate. The proposed research is centred on the effects of concrete thermal mass in different climatic regions. Two cities with distinct climates were identified in the study. Once again, this provides a limit towards generalisations for other climatic regions of South Africa and around the world. In addition, IWEC data files obtained through EP (EnergyPlus) considers average climate data compiled over many years. The results would therefore be expected to differ from performance under extreme weather conditions which deviate from the average climatic data.

Lastly, in terms of building envelope efficiency, SANS 10400-XA:2011 and SANS 204:2011 highlight the requirements for compliance with maximum annual energy consumption per building classification with little guidance on thermal mass as a passive energy intervention. To influence these standards, this study will be able to initiate further in-depth research to standardize thermal mass as a passive design intervention requirement.

1.10 Definition of key terms

Climate Consultant: A graphic-based computer program that assists in understanding local climate regions by translating raw climate data into meaningful information represented on graphs and charts.

Compressive strength: The resistance of a material to break under compression. In particular, the compressive strength of concrete depends on various factors such as cement type, water-cement ratio as well as quality control during construction. Compressive strength is reported in units of megapascals (MPa).

Cooling energy loads: Cooling loads are defined as the amount of heat that must be removed from the room air to maintain a constant room air temperature at a given thermal comfort level.

Energy Use Intensity (EUI): Energy use intensity is defined as the measurement of a buildings' annual energy consumption relative to its square meterage. Essentially, buildings with a higher EUI use more energy per m^2 than buildings with a lower EUI. Energy efficiency regulations are therefore commonly benchmarked with EUI.

Heating energy loads: Heating load is the amount of heat that must be added to the room air to maintain a room air temperature at a given thermal comfort level.

Integrated Environmental solutions Virtual Environment (IES_VE): IES_VE is a software modelling and analysis programme used for the designing and operating of energy efficient buildings. For this study the programme will be used to simulate (through the heat balance method) the monthly cooling loads and heating loads in order to evaluate the thermal comfort conditions within the buildings under investigation.

IWEC data files: Typical weather files suitable for the use with building energy simulation. This climate data can be accessed through the EnergyPlus website. IWEC data files are derived from weather data captured on an hourly basis over many years. (ASHRAE, 2001) and (U.S. DOE, undated)

Lightweight concrete: Lightweight concrete (LWC) is defined by a dry density range of between 800Kg/m^3 and 2000Kg/m^3. Compared to normal weight concrete, it has a low thermal conductivity and compressive strength. (El Zareef, 2010)

Relative humidity: Relative humidity is the amount of water vapor in the air, expressed as a percentage of the maximum amount that the air could hold at the given temperature. It is the ratio of the actual water vapor pressure to the saturation vapor pressure.

Specific heat: Specific heat expresses the heat storage capability of a material per unit mass (J/kg °K) It is described as the amount of heat (Joules) energy required for raising the a unit of mass by one degree of temperature of a unit mass of a material by one degree Kelvin (°K).

Thermal conductivity: Thermal conductivity is the measure of heat flow through a unit thickness of a specific material, measured in W/mK. Greater conductivity results in less resistance to heat flow. Therefore, materials with a low thermal conductivity generally have good insulation properties.

Thermal diffusivity: Thermal diffusivity is the measure of thermal inertia of a given material. It is the ratio of thermal conductivity to the specific heat capacity at constant pressure and has the unit measure of m^2/s.

Thermal mass: 'Thermal mass depends on density and specific heat of the materials and it measures the heat storage capacity of an element (Arcuri *et al*., 2016:122). The various factors that influence thermal mass behaviour include: thermal conductivity (K), thermal diffusivity (α) and specific heat capacity (C) (Asadi *et al*, 2018).

1.11 Structure and chapter outline of study

This report comprises of six chapters as outlined in this section. The content of each chapter is briefly summarised. In addition, the overview of the substantive chapters also indicates the sub-questions being addressed in the respective chapter.

Chapter 1: Introduction

Chapter 1 provides insight into the background of the study and includes the problem statement, objectives, rationale of the study as well as the research question, sub-questions and the working hypothesis. Firstly, the chapter provides the introduction and sets up the framework of the study in order to place the research in context (both theoretically and empirically). Furthermore, it provides a systematic and logical approach towards the problem statement. The objectives and rationale of the study lead to the main research question and sub-questions which were used as a guideline for the study. Finally, a working hypothesis is outlined followed by limitations of the study.

Chapter 2: Literature review

Chapter 2 reviews literature evaluating thermal mass and its influence on building energy performance and indoor thermal comfort. Furthermore, studies on the relationship between structural performance and thermal properties of heavyweight and lightweight concrete are reviewed. A conceptual framework is presented at the end of the chapter, outlining the structure and direction of the study. Sources include academic books, journal publications, dissertations, building design standards as well as electronic sources.

Chapter 3: Research methodology

Chapter 3 substantiates on the research methodology as well as the process taken during the study approach with regards to data collection and consolidation. The chapter provides details on the procedural steps and analysis and includes a summary of the collection tools (identifying primary and secondary data sources) to conduct the investigation in relation to the sub-questions highlighted in section 1.7.2.

Chapter 4: Case study buildings overview – Macro-climate and micro-climate investigation and the influence of daily and seasonal temperature cycles on thermal comfort within buildings.

Chapter 4 focuses on the climatic characteristics of the different regions chosen for the study. Climate data from IWEC files were collected and collated through Climate Consultant software tool for both Johannesburg and Durban. Further analysis and interpretation of climatic data through psychrometric charts were conducted towards the substantiation of sub-question 1. A discussion on the micro-climate factors was carried out. In addition, the influence that seasonal temperature cycles have on the thermal comfort was assessed, including various options to passively regulate the thermal environment within office buildings.

Chapter 5: Data analysis and findings- Structural and thermal properties of concrete due to thermal mass variations in line with thermal comfort needs.

Chapter 5 presents the existing case study buildings as modelled and interpreted on the IES_VE software tool. Climate data, building composition, solar radiation and various energy loads from internal gains were applied as input values into the building models, with a variation of concrete density. The models were analysed in order to derive the overall heating and cooling energy loads required within each case study building. Results were graphically represented and analysed to substantiate sub-questions 3 and 4. Complete and comprehensive data analysis and interpretation of the results were conducted, including the total energy saving acquired from the use of heavyweight versus lightweight concrete construction and its feasibility.

Chapter 6: Consolidation, conclusions and recommendations

Chapter 6 consolidates all the sub-findings and substantiates the main research question of the study through the assessment of the sub-questions defined in Chapter 1. A section outlining recommendations for further areas of research was also included.

Chapter 2: Literature review.

2.1 Overview

This chapter provides a literature appraisal focusing on the influence that thermal mass has on building energy performance. The introduction highlights that building operational energy is primarily required for cooling and heating, specifically in office buildings. Focus is then drawn to building energy performance. The modes of external to internal heat transfer through buildings are reviewed, with specific focus on climate considerations and thermal mass of buildings. Background literature on human comfort and the influence of daily and seasonal climate cycles on thermal comfort within buildings are reviewed in Appendix A. This will assist in gaining insight into the factors influencing micro-climates and macro-climates in relation to a building's geographical location (see Appendix A). The chapter then continues to review studies on the relationship between structural performance and thermal properties of high thermal mass construction materials. Studies on lightweight and heavyweight concrete thermal mass used in construction and its influence on building thermal comfort are also appraised.

2.2 Introduction

In recent years, the conservation of energy in buildings through energy efficiency has gained importance on account of greenhouse gas emissions and climate change. Buildings are responsible for more than 40% of global energy use and 30% of greenhouse gas emissions are attributed to the construction and operation of buildings (Asadi *et al*, 2018) and (UNEP_SBCI, 2009). Building energy consumption is categorised into embodied energy and operational energy. Majority of the operational energy is primarily required for cooling and heating to achieve a comfortable indoor thermal environment for human occupation. Specifically, in office buildings, a significant proportion of total building energy consumption can be attributed to HVAC systems. Figure 1 illustrates the typical energy consumption breakdown in an office building. Operational energy of the HVAC systems accounts for 39% of the total energy consumed. This highlights the need for the design and construction of more energy efficient buildings, which focus specifically on reducing HVAC energy loads required to achieve indoor thermal comfort. (HVAC HESS, 2013)

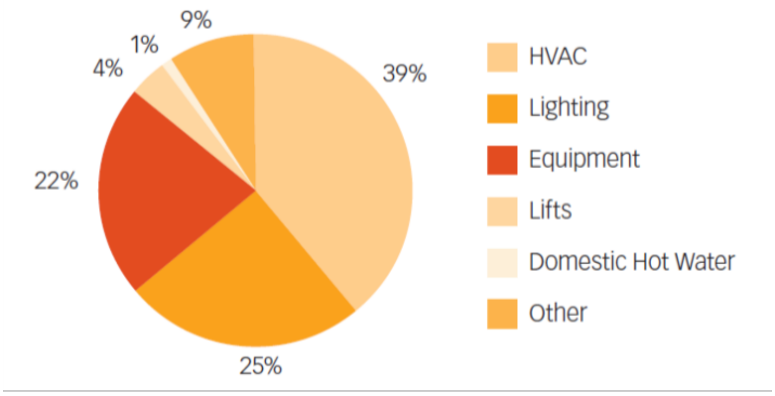

Figure 1: Typical energy consumption breakdown in an office building. (HVAC HESS, 2013:2)

2.3 Building energy performance - modes of external to internal heat transfer

Pedersen (1997) and (Tosh, 2017), note that the investigation of building performance involves the analysis of three modes of external to internal heat transfer which are; radiation, conduction, and convection. These modes of heat transfer occur simultaneously, whereby solar energy is absorbed by the exterior face of the building in the form of heat. Through conduction, the heat transfers to the inside of the building. However, due to thermal mass of the building envelop, heat is captured and is slowly released/radiated into the building over time. Optimising the thermal mass to align with building heat transfer could have significant effects on the overall heating and cooling requirements within a building. Convection is the transfer of heat resulting mainly through the movement of air of different temperatures. The movement of air in buildings can be forced (driven by sources of heating or cooling) or natural due to pressure differences from one part of the building and another. Finally, radiation is defined as the heat transfer between objects at different temperatures. Objects continuously lose and gain energy by emitting and absorbing electromagnetic energy from around them. The combination of these modes of heat transfer through the building envelope together with influencing factors such as building envelope systems, indoor internal heat gains, natural air exchanges and HVAC systems, contribute towards attaining balanced heat distribution within a building.

Figure 2 illustrates a simplification of the heat balance method when ultimately calculating the balance of energy required for heating and cooling while factoring the modes of heat transfer. This essentially entails four stages which includes the outside face heat balance, the surface or wall conduction process, the inside face heat balance, and finally the air heat balance. As depicted in Figure 2, various factors influence heat gain and reduction at every stage and the overall outcome being an internal consistent thermal environment. (Pedersen *et al.*,1997)

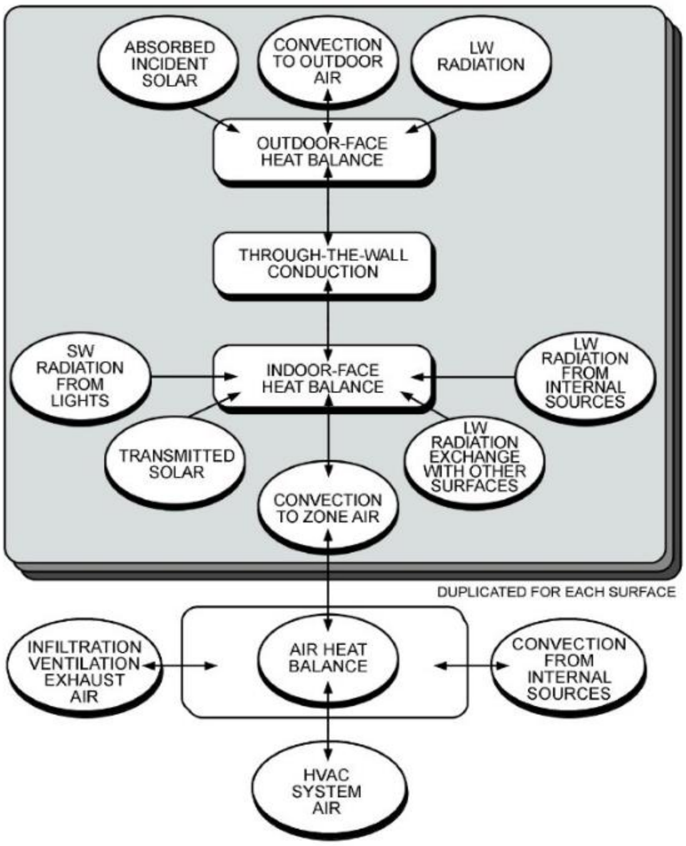

Figure 2: Schematic of the heat balance method (Pederson 1997:461)

2.4 Thermal mass and its influencing factors

The effective use of thermal mass can considerably contribute to the sustainability of buildings especially through energy conservation during the operational stage. In this regard Asadi *et al.*, (2018:14) notes that “Thermal comfort is greatly dependent on the thermo-physical properties of the building construction materials employed.” Depending on the climatic conditions there are many advantages in utilising the energy storage capabilities of thermal mass elements in buildings. It is an essential and complementary component of passive solar design, whereby solar radiation and thermal heat energy is absorbed by buildings during the day and is gradually released into the building overnight. The extent to which thermal mass can reduce heating and cooling energy loads in a building is dependent on a number of interrelated factors such as climatic conditions, internal gains, orientation of the building, the area and positioning of fenestrations, occupancy patterns as well as the type of HVAC system (Hensen *et al*. 2016). Optimising a building’s thermal mass may result in benefits which include enhanced fabric energy efficiency and a reduction in carbon emissions over the operational stage of the building. This would mainly be due to the reduced energy loads required for heating and cooling, which relates directly to cost savings, reduction in the need for more expensive low and zero-carbon technologies to meet CO_2 targets and potential for improved property resale value. Deciding on an adequate level of thermal mass would therefore constitute a significant strategy towards the pursuit of the expected energy efficiency gains. (Arcuri *et al*, 2016) and (Chel and Kaushik, 2017).

2.4.1 Thermal mass properties of construction materials, with specific reference to the ability of concrete as a thermal mass.

Thermal mass is defined as a material's ability to absorb, store and release heat. Density (*p*), thermal conductivity (K), thermal diffusivity (α) and specific heat capacity (C) are some of the factors influencing thermal mass behaviour (Asadi *et al*, 2018). High specific heat capacity and high density within a material allows for maximum storage of heat, while a moderate thermal conductivity is usually favourable so that the rate of heat flow in and out of the material is approximately in step with the daily heating and cooling cycle of the building. (De Saulles, 2012)

It is understandable that thermal mass elements contain inherent qualities for both heating and cooling. Denser materials tend to absorb more heat energy which dissipates over a period of time. Thermal mass can be utilised as a means for basic passive solar design where available heat is absorbed and stored for subsequent distribution into a building when air temperature drops.

Table 1 highlights common building materials used in the construction industry. Lightweight concrete is identified as a thermal mass material which has a high specific heat capacity, a moderate density as well as a moderate to low thermal conductivity. On the other hand, normal weight concrete (which is classified as heavyweight concrete in this study), allows for a greater storage of heat due to its density, however it is weak in terms of its thermal conductivity properties. While brickwork seems to compare well to lightweight concrete in terms of its thermal properties, it is not as versatile as heavyweight concrete or lightweight concrete as a high strength structural material.

Table 1: Thermal properties of common construction materials. Source: Adapted from (Wilson, 2008).

Building material	Specific Heat capacity (J/kg.K)	Thermal conductivity (W/m.K)	Density (kg/m^3)	Effective thermal mass
Hardwoods (oak)	1250	0.16	720	Low
Steel	450	50	7800	Low
Brick	840	0.7	1600	Medium-High
Concrete cast (normal weight)	1000	1.75	2300	High
Concrete cast (lightweight)	1000	0.4	1200	Medium-High

Concrete is one of the most widely used construction materials for all building types. The addition of reinforcement steel in concrete forms structural members that are able to resist many types of loading. The combination of concrete and reinforcing steel results in a structural material with complementary strengths, where concrete resists compression forces and steel reinforcement resists tension forces (Al-Manaseer and Hassoun, 2012). In addition, concrete has high thermal mass properties. It has a generous heat storing capacity for effective usage in buildings which suggests that it is a favourable construction material in passive design for energy efficiency in buildings (The European concrete platform ASBL, 2007). The next section focuses on the structural performance of heavyweight and lightweight concrete versus its inherent thermal properties.

2.5 Properties of normal/heavyweight concrete versus infra-lightweight and lightweight concrete as thermal mass.

The performance of concrete as a building material is based on its constituents. For normal hardened concrete, the unit weight is dependent on the grading and size of aggregates, water-cement (w/c) ratio, as well as the strength of concrete. The workability of the concrete mix is then checked for adequacy through slump testing when used on site. Al-Manaseer and Hassoun (2012) approximates the density of standard structural hardened concrete (with an aggregate size of approximately 20mm and concrete strength between 25-30MPa) to be between $2320kg/m^3$ and $2400kg/m^3$.

Fanourakis (2014) conducted an experiment, assessing the properties of six standard structural concrete mixtures using natural 19mm quarried aggregates (quartzite, granite and andesite), with a w/c ratio of 0.56 and 0.4 for concrete mixtures 1 and 2 respectively. Figure 3 shows the mix proportions and corresponding test results. It is evident that mix proportions with a w/c ratio of 0.56 yield a concrete cylinder compressive strength of 30MPa, whereas a 0.4 w/c ratio yields a much higher compressive strength of 50MPa. The densities of all six mixtures range between 2371kg/m^3 to 2596kg/m^3. Therefore, the density of standard hardened structural concrete, using readily sourced natural aggregates, can be approximated to 2400kg/m^3.

Aggregate Type	Quartzite		Granite		Andesite	
Mix Number	Q1	Q2	G1	G2	A1	A2
Water (l/m^3)	195	195	195	195	195	195
CEM I 42,5N (kg/m^3)	348	488	348	488	348	488
19 mm Stone (kg/m^3)	1015	1015	965	965	1135	1135
Crusher Sand (kg/m^3)	810	695	880	765	860	732
w/c Ratio	0,56	0,4	0,56	0,4	0,56	0,4
a/c Ratio	5,24	3,50	5,30	3,55	5,73	3,83
Slump (mm)	90	50	115	70	95	55
Cube Compressive Strength (MPa)	37	65	38	65	48	74
Cylinder Compressive Strength (MPa)[a]	30	53,5	30,7	53,5	38	59
Characteristic Cube Strength (MPa)	30	50	30	50	30	50
Characteristic Cylinder Strength (MPa)[a]	25	40	25	40	25	40
Concrete Density (kg/m^3)	2371	2410	2385	2432	2596	2585
Average Elastic Modulus of included Aggregate (GPa)	73		70		89	

[a] Inferred from cube strength using the conversions from EC 2 (2004)

Figure 3: Concrete mix proportions with varying natural aggregates and corresponding strength results. (Fanourakis,2014:4)

There has been an abundance of research conducted into structural concrete, especially towards optimising concrete mixtures to suit diverse structural performance goals. However, research into lightweight concrete may not be as advanced, in spite of its favourable mechanical and thermal properties (El Zareef, 2010). In line with the German structural concrete design standard DIN 1045-1:2008, various types of concrete are defined and classified according to their densities as shown in Figure 4. Infra-lightweight concrete (ILWC) is defined as concrete with dry densities in the range below 800kg/m^3, whereas lightweight concrete (LWC) is defined as falling within the density range of between 800kg/m^3 to 2,000kg/m^3. On the other hand, normal weight concrete (NWC) falls between the density range of 2,000kg/m^3 to 2,600kg/m^3, and heavyweight concrete (HWC) is defined as having a density above 2,600kg/m^3.

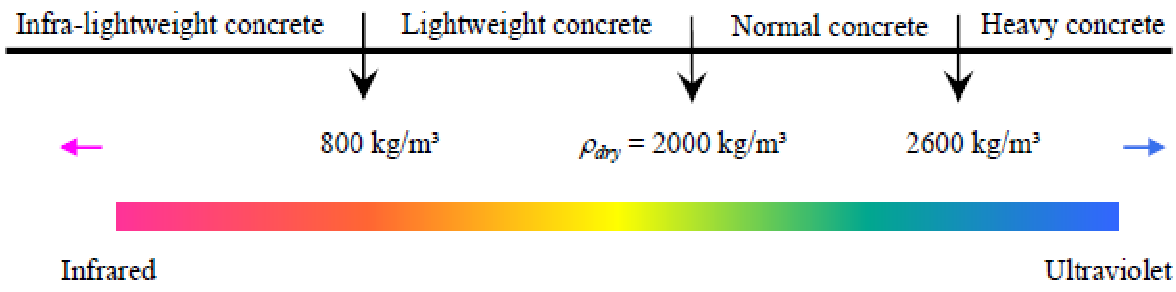

Figure 4: Classification of concrete according to German code DIN 1045-1. (El Zareef, 2010:23)

The recent trend towards lightweight concrete construction is particularly interesting as benefits of material efficiency and savings in embodied energy are observed, without significantly compromising on the strength of the material (Hensen, *et al.*, 2016). Asadi *et al* (2018) indicates that structural lightweight concrete, which contains lightweight aggregates have low thermal conductivity (K) and a high specific heat capacity (C) compared to heavyweight concrete containing conventional aggregates. This suggests that the heat transfer rate of structural lightweight concrete is relatively lower than heavyweight concrete. Similarly, a study conducted by Oktay *et al* (2015), indicates that thermos-physical properties of concrete are directly linked to the type and strength of the aggregate that it contained. Results showed that lightweight aggregate concretes with densities between 1168Kg/m^3 – 2345kg/m^3, resulted in compressive strength between 5MPa to 50MPa. Moreover, lightweight aggregate replacements into normal concrete showed a reduction in thermal conductivity of concrete and hence an improvement in the insulation properties. El Zareef (2010) further describes the classification of lightweight aggregate concretes. Figure 5 highlights various densities of lightweight concrete based on different aggregate types. Lightweight concrete made with aggregates such as vermiculite and perlite are considered low strength with densities varying between 350kg/m^3 to 1150kg/m^3. Similarly, natural aggregates such as pumice and scoria are used to form a moderate strength lightweight concrete with densities ranging between 800 kg/m^3 to 2000 kg/m^3. Lastly, expanded slag, shale, clay and slate are used in lightweight concretes with densities ranging between 1400kg/m^3 and 2000kg/m^3.

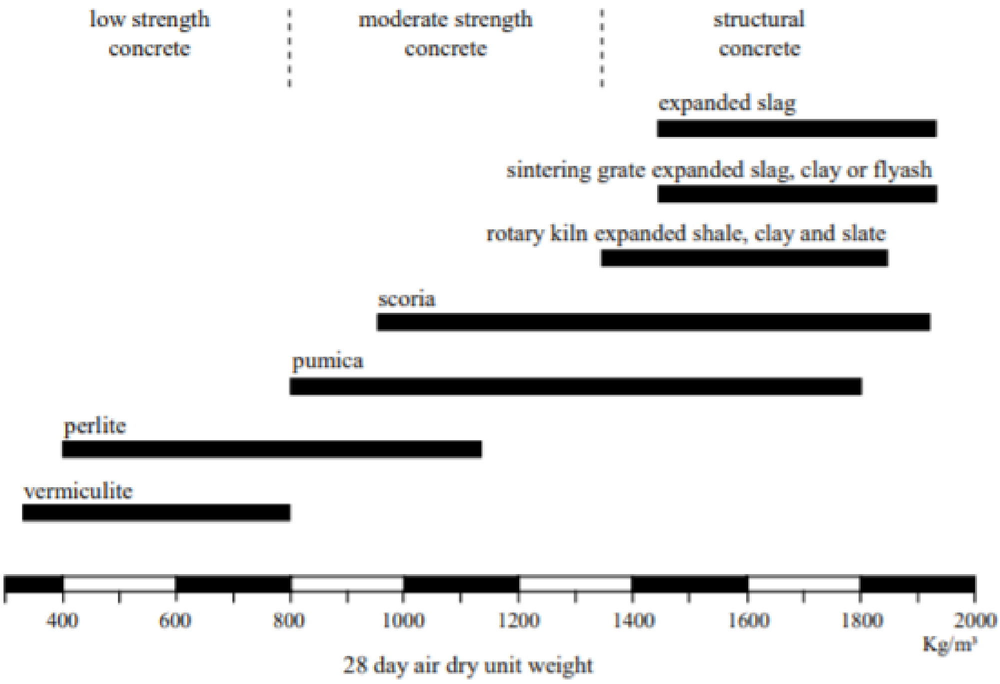

Figure 5: Classification of lightweight aggregate concrete based on its unit weight. (El Zareef, 2010:7)

Investigation into lightweight concrete has shown that there are advantages to its application. These include reducing the overall dead load of a structure and providing basic insulation properties when compared to heavyweight concrete (El Zareef, 2010). From a structural perspective, in order for lightweight concrete to be compatible with heavyweight concrete it requires adequate compressive strength (measured in MPa or N/mm^2). Figures 6 and 7 represent the relationship between lightweight concrete density relative to concrete strength and thermal conductivity. The density of concrete is proportional to both compressive strength and thermal conductivity. Experimental results support the view that ILWC density at $800kg/m^3$ has a compressive strength of approximately 8MPa and a thermal conductivity of 0.4W/mK, whereas concrete density at $2{,}000kg/m^3$ has a compressive strength of approximately 90MPa and a thermal conductivity of 1.6W/mK. Based on Figure 6, a lightweight concrete with a density of $1200kg/m^3$ to 1300 kg/m^3 would result in a compressive strength of approximately 25-30MPa. (El Zareef, 2010)

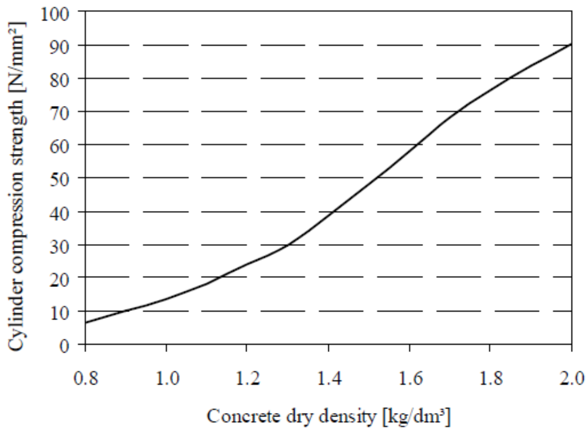

Figure 6: Lightweight concrete density in relation to compressive strength. (El Zareef, 2010:20)

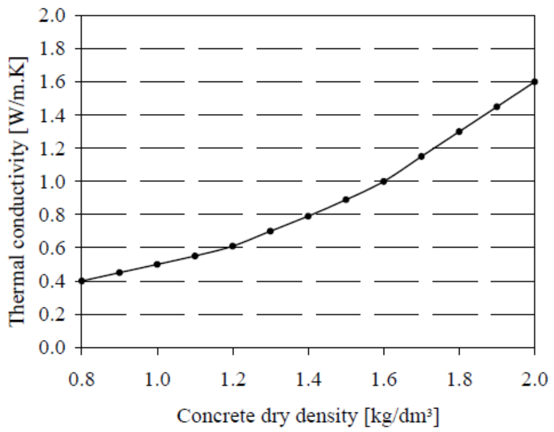

Figure 7: Lightweight concrete density in relation to thermal conductivity (El Zareef, 2010:20)

Focusing specifically on the material properties of ILWC and LWC, El Zareef (2010) concludes that although ILWC possesses favourable insulation properties, it is relatively weak as a structural material with low compressive strength and high concrete shrinkage and creep values. Also, the fabrication costs of ILWC are higher when compared to other concrete types. On the other hand, LWC showed favourable results in terms of its structural performance. From cube strength tests conducted, LWC with a density of 1,250kg/m^3 obtained a compressive strength of 28MPa and a relatively low thermal conductivity of 0.6W/mK. This shows that lightweight concrete has the advantages of performing well structurally while exhibiting good insulating properties at the same time. (El Zareef, 2010)

Similarly, Hensen *et al.*, (2016) reported on energy efficiency and thermal comfort in ultra-light weight concrete construction with a density of 800kg/m^3 and a thermal conductivity of 0.14W/mK as well as a compressive strength of 10MPa. Although this weight to strength ratio is relatively good, it is not as structurally viable as the properties exhibited by LWC.

In order to complement the design of energy efficient buildings, properties of structural materials such as strength and stiffness should be considered alongside thermal properties so that the overall thermal performance of buildings are optimised from project inception stage.

2.6 Structural performance versus thermal properties of high thermal mass construction materials.

The stability and structural performance of a building is first and foremost the priority of construction. However, adapting these structural materials to influence thermal performance for energy efficiency can be valuable in terms of energy and cost savings.

2.6.1 Structural performance of heavyweight and light weight concrete

Stress analysis of construction materials is an important component of structural engineering. Failure of structures is usually caused by excessive stress exerted on a structure. According to Case *et al* (1999), the strength of a material is defined largely by the internal stresses that a material can handle. Knowledge of these stresses is essential in the design of safe and stable structures. Typical strength properties are shown in Table 2.

Table 2: Approximate strength properties of engineering materials. Source: Adopted from (Case *et al*., 1999:37)

Material	**Density (kg/m^3)**	**Ultimate strength (MPa)**	**Young's Modulus (MPa)**
Concrete	2410	30 (compression) 3 (tension)	14 000
Medium strength steel	7840	370	200 000

Concrete is a highly versatile and durable structural material, which is widely used in construction. As highlighted in Table 2, concrete has a high compressive strength which is favourable in construction. Although it may be low in tensile strength, this is commonly overcome through reinforced concrete design. It is evident that the strength capacity of steel is higher than concrete. In addition, the self-weight of steel is light compared to concrete, thus allowing for a very appealing strength to weight ratio. However, when compared to steel, concrete is inexpensive. It uses natural raw materials in its composition and its poor strength to weight ratio can be improved by reducing its self-weight through the introduction of lightweight (low density) concrete. (Goode *et al*, 2017)

Lightweight concretes can either be lightweight aggregate concrete, foamed concrete or aerated concrete (AAC). For the purposes of this study lightweight aggregate concrete was investigated. There is a large variety of lightweight aggregates used in concrete and the type of aggregate used will determine the concrete density achieved. Aggregate density range is shown in figure 5. This means that higher concrete strengths can be achieved from denser aggregates which will favour the overall structural design. On the other hand, aerated/foamed concrete is when gas is introduced to the mortar mix within concrete. This is generally used more as a non-structural concrete for filling voids in infrastructure or are produced in the form of pre-cast blocks. (Taylor, 2013)

Lightweight substitution is usually made to obtain a lower density and self-weight while maintaining properties broadly similar to normal weight concrete. These lightweight aggregates make use of an internal microstructure of air-filled voids to lower its bulk densities compared to heavyweight concrete that typically has no voids (Juan, 2011). Low density lightweight concrete therefore possesses enhanced thermal insulation properties compared to heavyweight concrete. This means that heat does not easily penetrate through the material, thus allowing more regulation capabilities within the building.

Even though thermal properties of lightweight concrete exceed those of heavyweight concrete, its structural performance does not match the capabilities of heavyweight concrete. There are two main trade-offs involved in the utilisation of lightweight concrete instead of normal weight concrete. Firstly, lightweight concrete may have a lower elastic modulus (the ratio of the applied stress to the corresponding strain within the elastic limit). It indicates a material's resistance to being deformed when a stress is applied to it. Modulus of elasticity also indicates the stiffness of a material. For stiffer materials the value of elastic modulus is higher. (Juan, 2011)

According to the American concrete structural design standard, (ACI318-08, 2007:107), the modulus of elasticity for concrete (Ec), measured in megapascals (MPa), is defined by the equation below:

$Ec = wc^{1.5} \times 0.043\sqrt{fc}$ ……………………………………………….....(A)

Where wc = density of concrete which is specified between 1440 kg/m^3 and 2560 kg/m^3 and fc = concrete strength (MPa)

It clearly shows that the density of concrete is directly proportional to the elastic modulus thus indicating that lower density materials would have a lower elastic modulus. (AASHTO, 2010) concurs that modulus of elasticity of a given concrete depends on the density through the relative amounts of aggregate and paste within concrete composition. Lightweight concretes usually have a modulus of elasticity of about ½ to ¾ that of a heavyweight concrete. Elastic modulus of a material is an important component of structural deflection calculations. A lower elastic modulus in a material results in greater deflections across structural spans. As a result, lightweight concrete has lower tensile strength and subsequently, reduced shear resistance. (Juan, 2011)

In spite of these limitations, the value of lightweight concrete should not be disregarded since these weak properties can be overcome with the appropriate structural design and detailing. Afrisam (2018) notes that aggregate type can influence the modulus of elasticity of concrete mainly through the stiffness of the aggregate and its volume concentration. Figure 8 represents various types of South African aggregate materials and their corresponding strength as well as elastic modulus. It is evident that elastic modulus and compressive strength are linearly proportional.

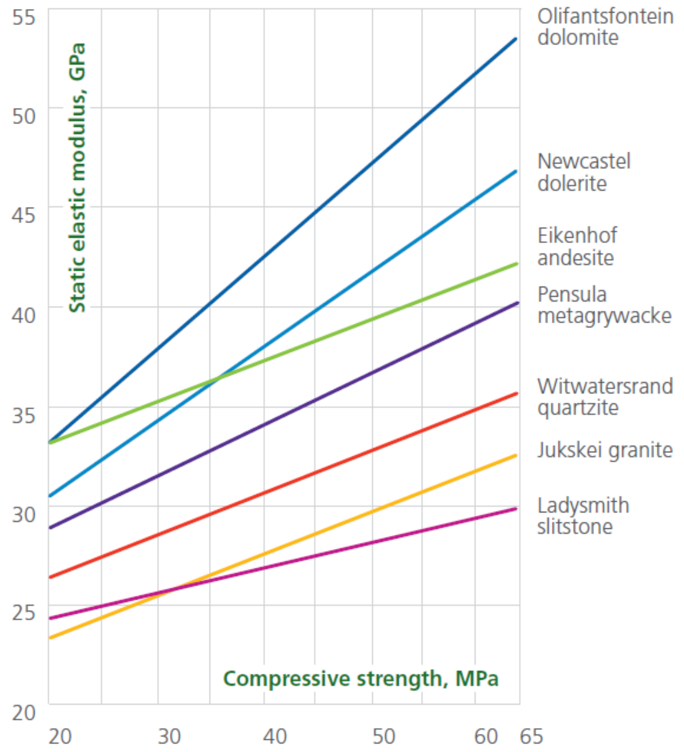

Figure 8: Static elastic modulus vs compressive strength of concrete for 3 to 28 days. (Afrisam, 2018: 117)

The immediate benefits of lightweight concrete construction should therefore be taken advantage of when constructing energy efficient buildings from inception. These benefits include improved thermal properties which can translate to reduced energy loads required for heating and cooling. Improved fire resistance, reduction in formwork and propping on site as well as significant reduction in dead loads thus allowing for cost savings in the volume of concrete material used. However depending on the structural design allowance, extra reinforcement may become necessary. It should also be noted that the demand for lightweight concrete would initially be lower compared to heavyweight concrete which translates into higher costs per m^3.

2.7 Climate considerations and thermal mass

Climate considerations are critical in the effective use of thermal mass. As highlighted previously, when thermal mass is incorporated effectively into building design it assists in achieving internal thermal comfort.

2.7.1 Effective incorporation of thermal mass for building energy efficient design.

During warm summer days, building construction materials with thermal mass will gradually absorb heat and store it until exposed to cooler air at night. Heat would be absorbed and released in response to the change in day and night-time temperature conditions. The ability to respond naturally to changing conditions would help stabilise indoor temperature and thus create a relatively self-regulating environment, while reducing the risk of overheating and the need for extensive mechanical cooling or heating.

During winter, thermal mass can also assist in regulating internal thermal conditions through the retention and recycling of heat. To effectively incorporate thermal mass in winter, the relationship between the internal heat gains and the ability of the building thermal mass to retain this heat must be understood. The retained heat in the building thermal mass can be used to reduce the energy needed to keep buildings warm during the winter season. The principle behind this relies on the ability of thermal mass to capture and recycle passive solar gains from north facing windows and internal thermal gains from lighting, equipment and occupancy. As the temperature drops, there would be a slow release of heat back into the building, thus reducing the requirement for supplementary heating to assure comfortable indoor environment. Whilst lightweight concrete buildings are also capable of doing this to a limited degree, the extent to which free heat gains can be recycled increases with the level of available thermal mass.

When considering both approaches it is evident that thermal mass is beneficial if night-time ventilation (or some other means of cooling) can be used to remove the heat absorbed by the building fabric during the hot hours, if so required. The passive benefits of thermal mass would be best optimised during the building design stage, largely toward mitigating overheating.

2.7.2 Circumstances where thermal mass is not beneficial.

As explained in Chapter 2.7.1, in order for thermal mass to be used effectively to reduce energy usage for heating and cooling, there must be a significant difference in day and night temperatures to allow absorption and dissipation of heat from the indoor air. In regions where there are no significant difference in day and night temperatures (low diurnal temperature range), buildings with high thermal mass, would in theory not offer significant energy efficiency benefits.

2.8 Studies analysing concrete thermal mass effects towards energy efficiency in buildings.

Specifically within office buildings, a significant proportion of energy is utilised for space heating. Presently, many office buildings are reliant on an entire air conditioned approach. However, with rising energy costs and CO_2 emissions, an energy efficient approach should be considered to maintain buildings at a comfortable state without using energy intensive interventions. The following section appraises studies that have considered optimising concrete thermal mass as a passive intervention to reduce the overall heating and cooling loads in buildings and thus improving energy efficiency.

Multi-variable studies have been conducted at different levels of detail to improve building design for energy efficiency. However, as the number of design variables increase during analysis, the level of complexity also increases. Li *et al.*, (2018), presents the optimisation of building envelope design by focusing on four different factors and based on an 'artificial neural network model' which entailed a multi-objective algorithm. These factors are thermal mass (in particular the thickness of concrete slabs), insulation levels, absorbance of solar radiation of exterior walls / roof, shading, the glazing ratio (also known as the window-to-wall ratio) and orientation. The impact of these factors on the thermal comfort of a building were as follows; '(1) thermal mass can affect the fluctuation of the daily temperature inside the building; (2) insulation can affect heat gain/loss by conduction through the opaque envelope; and (3) the absorbance of solar radiation of the opaque envelope and the location and size of the windows can affect the solar heat gain.' (Li *et al.*, 2018:1). It is clear from the study that the effects of thermal mass cannot be researched in isolation from the multi-variable elements of a buildings' envelope.

Reardon (2013), and the European concrete platform ASBL (2007) concur that materials with higher density (higher thermal mass) increases the thermal storage capacity of building components. This has the ability to contribute towards the optimisation of thermal comfort in buildings, especially in climate zones with a significant difference between maximum and minimum daily temperatures. The European concrete platform ASBL (2007) highlights the positive influence of thermal mass on the overall thermal comfort in a building. Approximately 2-15% savings in operation-stage energy consumption can be achieved within a building constructed from normal weight concrete compared to lightweight concrete. However, Hensen *et al* (2016) argues that future trends in sustainable buildings are gravitating towards the use of lightweight construction components. With benefits of material efficiency and related savings in embodied energy, it would be interesting to investigate the balance between thermal mass and the trend toward lightweight construction. Furthermore, NRMC(undated) concurs that structural lightweight concrete mixes can be designed to reach similar strengths to heavyweight concrete structures. The higher cost of lightweight concrete is compensated by the reduction in the overall volume of concrete required and dead load of the structure.

Kokogiannakis *et al*., (2017) explores the thermal storage capacity of heavyweight and lightweight concrete for office buildings. The research is further enhanced through the selection of an appropriate type of concrete construction (waffle slab vs flat slab) to determine the respective effects on the overall thermal comfort within a building. Using DesignBuilder energy simulation software for buildings, Kokogiannakis *et al*. (2017) was able to incorporate hourly climatic data values to take into account the effects of the climate at various case study locations. With reference to concrete form and construction type, the buildings were designed and simulated using four different construction types whereby a flat slab and waffle slab were designed independently with normal weight concrete and then compared with lightweight concrete (waffle / lightweight, flat/lightweight, waffle/normal weight, flat/normal weight). The results illustrated the energy usage for each building as well as cooling and heating loads across the buildings. The most significant findings of the study revealed that lightweight concrete waffle slabs (lower density and low mass concrete) requires more heating and cooling energy under all climate regions covered in the study. This is due to its faster response to external temperature changes. In contrast, significantly lower energy consumption figures were noted for buildings designed with normal weight flat slabs especially in colder climates. This is an expected result demonstrating the relationship between density of concrete and a building's thermal mass and how this contributes to energy savings. (Kokogiannakis et al., 2017)

Ghoreishi (2015) presents a similar investigation of quantifying the effects of concrete thermal mass towards energy efficient buildings where the two variables of concrete thermal mass and its effectiveness in reducing energy consumption in office buildings were investigated. Firstly, the thickness and distribution of concrete thermal mass in the building elements was assessed in relation to improving internal thermal comfort. Secondly, the distribution of thermal mass on the internal concrete elements is assessed in relation to improving thermal comfort. Comparison of the effects on these variables clearly demonstrate that thermal mass design emphasis needs to be on building envelopes instead of interior building elements such as slabs or interior wall systems. This is in contrast to the findings of Kokogiannakis *et al*., (2017) which demonstrated conclusive results in energy savings when analysing thermal mass concrete slabs only. Considering the findings in Ghoreishi (2015) and Kokogiannakis *et al*.(2017) it may be worthwhile to investigate the entire concrete thermal mass systems of a building in both the interior and on the building envelope.

In contrast, Kinnane and Reilly (2017) question the common assumption that high density (higher thermal mass) materials are inversely related to energy consumption within a building. Based on a new method of measuring the effects of thermal mass as opposed to relying on DesignBuilder simulation software modelling, the study quantifies the effects of thermal mass while including factors that would normally be excluded in the common modelling and simulation assessments so far. Through the use of this new method, thermal mass effects are assessed when comparing transient energy models (energy flow) to the conductivity values of building elements such as walls. The findings of this research conclusively demonstrate that high thermal mass materials are more effective in warmer climates whereas in colder high thermal mass may be a disadvantage, as it is likely to lead to increased energy consumption in order to achieve thermal comfort (Kinnane and Reilly, 2017). As previously highlighted by Hensen *et al*. (2016) and Li *et al.* (2018), there are several interrelated factors affecting thermal mass of a building which should be taken into consideration when determining the extent to which thermal mass can reduce heating and cooling energy loads in a building. Research based on existing buildings would have to find a means of analysis that incorporates various inter-related components of the building’s envelope into its analysis. DesignBuilder software offers such functions with advantages being that various components of the building envelope can be customised and the building design parameters can be adjusted for case specific modelling and simulation. As a result optimisation of the building’s design can be conducted using the software, suggesting that "the least amount of material can be determined to construct a building with a high indoor thermal comfort level and low thermal load." Li *et al*. (2018:3).

2.9 Feasibility of thermal mass in relation to energy savings within buildings.

Having appraised studies on the various properties and the effects of concrete thermal mass in buildings, it is important to assess the feasibility of optimised thermal mass as a passive intervention towards energy efficient buildings. Chen and Wang (2013), highlight the impact that thermal mass has on electricity savings for cooling buildings. Their study investigated energy savings achieved from varying the amount of concrete thermal mass in a typical mix-mode (combination of natural and mechanical) ventilation office building. In addition to thermal mass, other building envelope factors such as insulation, window opening area and climate were also incorporated into the analysis of mixed-mode ventilation performance. A cost-return analysis was then conducted to find the optimal thermal mass that yields the maximum return for the office buildings. The key findings from the study show that in Philadelphia (where the daytime temperatures during summer are high and the night temperatures low) increasing the thickness of concrete would yield no improvement in energy savings. Figure 9 illustrates the financial benefits of utilising thermal mass over 50 and 100 years respectively. The total financial return was calculated by taking into account the cost of concrete (thermal mass) and the reduced electricity consumption due to the addition of thermal mass. As seen in Figure 9, it is evident that there is an optimum concrete thickness that yields the highest return. A similar analysis was conducted for extremely hot climates in Phoenix and Miami. The addition of thermal mass was not beneficial in these climate regions because of consistently high temperatures above the comfort level. (Chen and Wang, 2017).

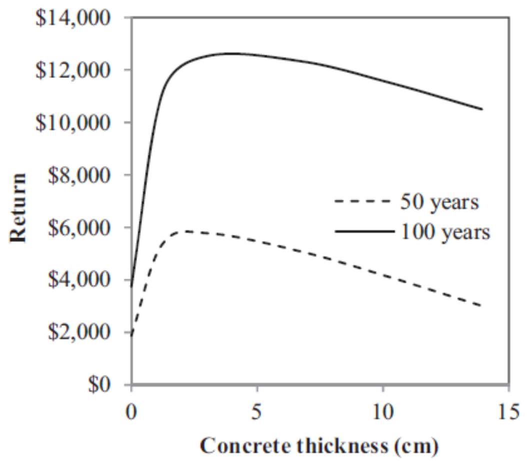

Figure 9: Monetary return from energy savings over different building lifetimes in Philadelphia. (Chen and Wang, 2017:271)

In terms of the economic feasibility of thermal mass, there are definite cost savings when thermal mass is optimised during the building design stage. These savings are realised from the return on energy savings when considering heating and cooling required to attain indoor thermal comfort (Chen and Wang, 2017). Although the cost of certain materials such as lightweight concrete may be higher than conventional heavyweight concrete, it would be compensated to some extent by a reduction in dead load of the structure.

2.10 Conclusion

From the literature reviewed it is evident that thermal mass can reduce energy consumption in buildings when designed in conjunction with its influencing factors. Climate considerations are critical in the effective use of thermal mass. Higher density thermal mass material respond better when the difference in day and night temperatures are significant, whereas lighter, less dense construction materials respond better to consistent temperatures.

Focusing on variations of concrete thermal mass, studies have shown lightweight concrete to have good thermo-physical properties. In particular lightweight aggregate concrete is favourable over heavyweight concrete as it exhibits better insulting properties and reduces the overall dead weight of a structure. Even though lightweight concrete is structurally weaker than heavyweight concrete, its inherent strength is high enough to perform well structurally.

From the insights gained, assessment of climate and temperature cycles as well as building material selection is vital to the design optimisation of thermal mass. The following chapters build on the literature reviewed to assess case specific office buildings with heavy and lightweight concrete thermal mass variations, in Johannesburg and Durban respectively.

2.11 Conceptual Framework Diagram

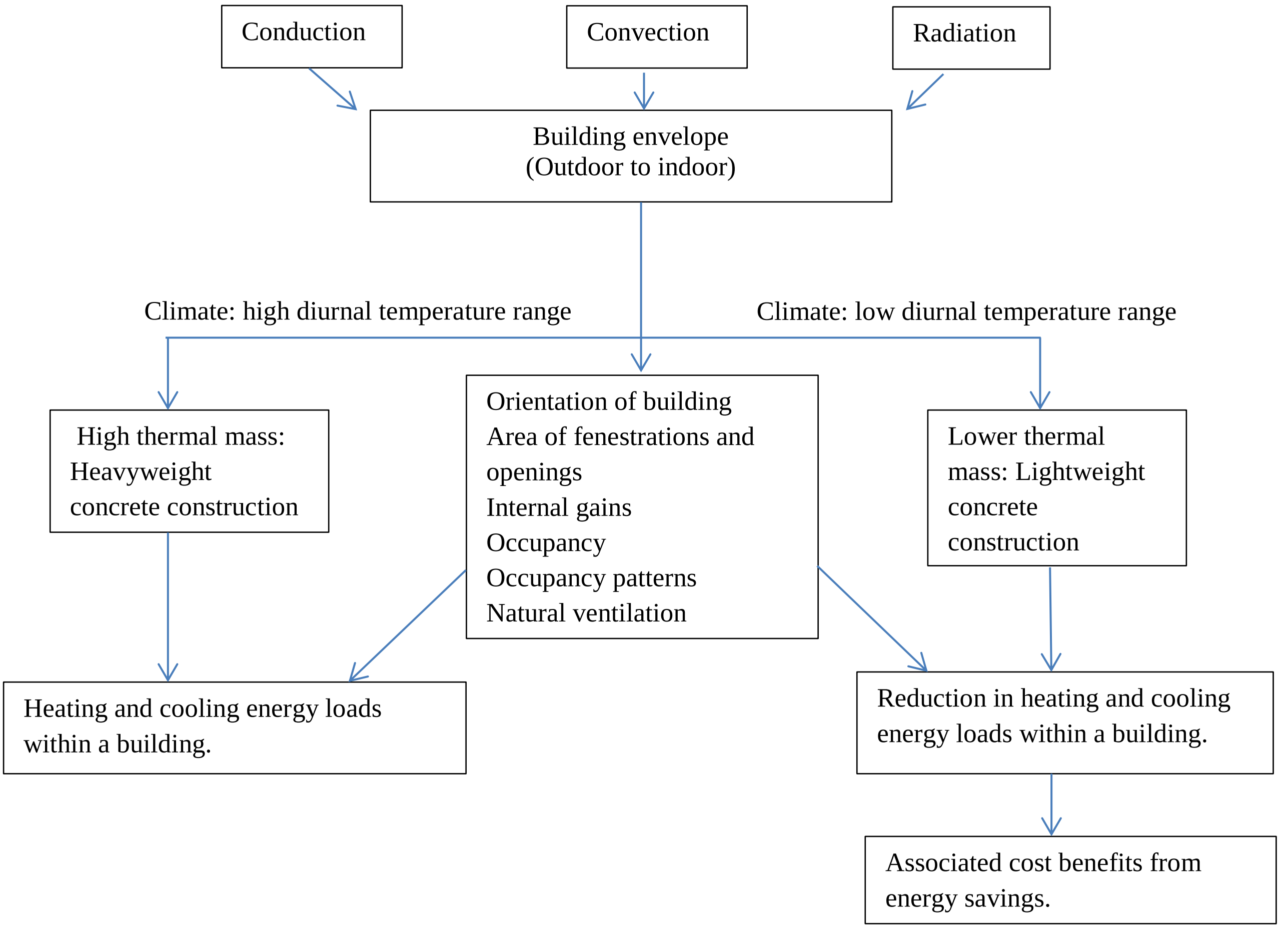

Figure 10: Conceptual Framework of the study

The conceptual framework shown in Figure 10 illustrates a working hypothesis and intent for the study based on the literature reviewed. The climate and influencing factors on the building will determine the overall heating and cooling energy loads.

Chapter 3: Research Methodology.

The study adopted a quantitative research approach in order to quantify the heating and cooling energy loads of the existing office buildings and compared them to a similarly modelled structure with a lower density, lightweight concrete thermal mass. The output assessed the balance between baseline heavyweight thermal mass concrete and lightweight concrete without compromising the structural integrity of the building. This entailed a parallel analysis of two case study buildings subject to different climatic regions within South Africa. An overall research process for the study was designed to guide the study through four steps; (1) climate assessment, (2) modelling and stimulation of case study buildings under investigation, (3) analysis and interpretation of simulations and (4) viability and feasibility evaluations of thermal mass variations. This chapter also summarises the tools and processes required to collect and analyse primary and secondary data in relation to the sub-questions presented in section 1.7.2.

3.1 Research process

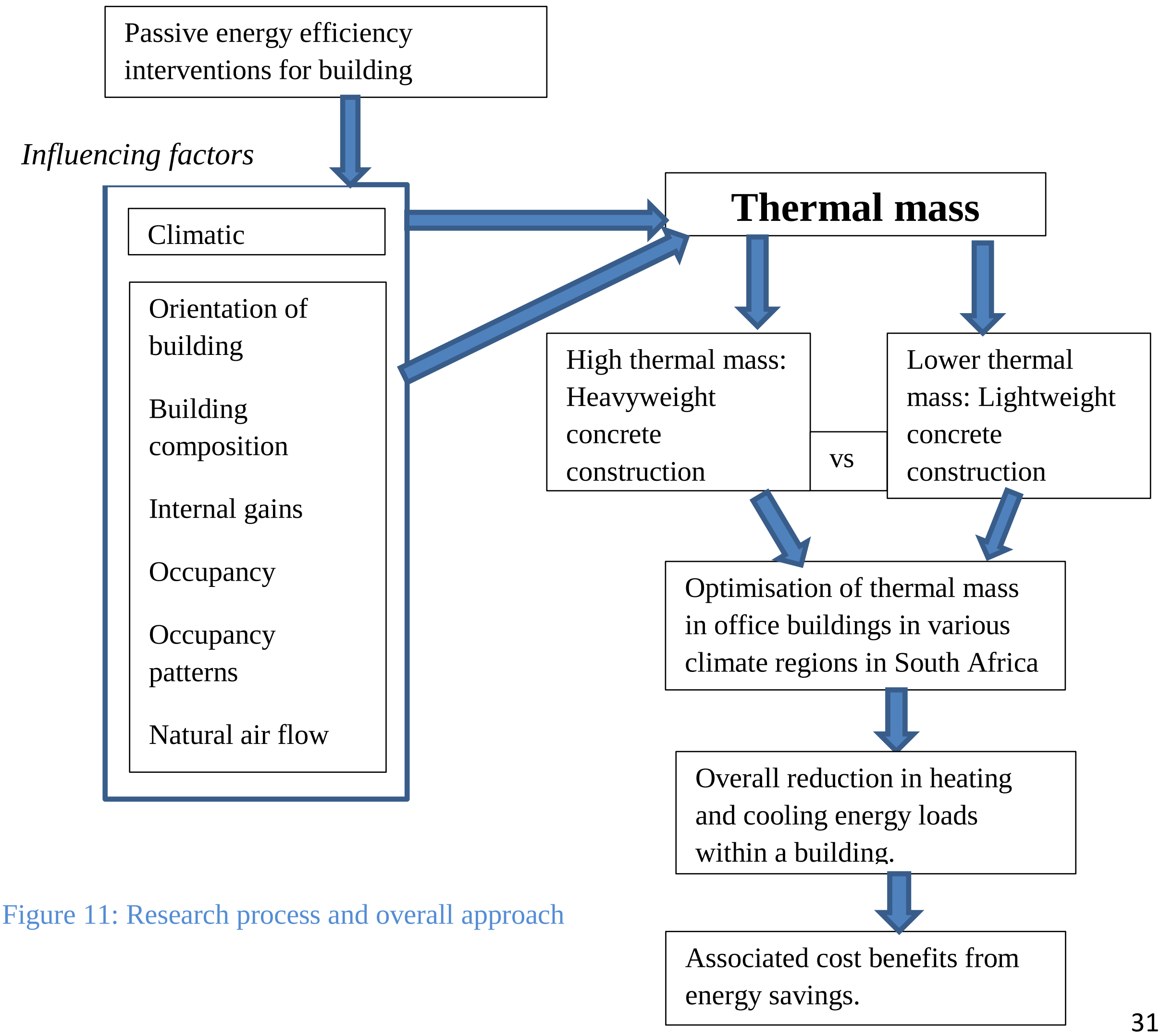

Figure 11: Research process and overall approach

The process diagram shown in Figure 11 highlights the overall research process for the study, which is guided by the following four steps:

Step 1: Assessment of the macro and micro climates for the case study regions.

Climate conditions for Johannesburg and Durban were chosen as the focus of the study for two main reasons. Firstly, they experience a vast difference between temperature cycles and other climate factors such as humidity, thus widening the scope of this investigation and allowing a basis for comparison. Given that, the focus of the study is an analysis and assessment for office buildings, Johannesburg and Durban both have a diverse pool of commercial and retail buildings. Through the study of psychrometric charts, climate data (as secondary data) were assessed to develop a comprehensive understanding of the daily and seasonal temperature cycles and macro climate conditions. Furthermore, micro climate factors were identified for each study. The assessment of both macro and micro climates aided in identifying potential passive energy efficiency interventions for the buildings under investigation. The analyses were then applied to assess the relevance of thermal mass towards optimum indoor thermal comfort with a view to energy efficiency.

According to energy efficiency regulations SANS 10400-XA the climate regions for Johannesburg and Durban are classified according to Figure 12. Johannesburg falls within the ‘cold interior’ zone, whereas Durban’s climate is categorised as a sub-tropical costal region.

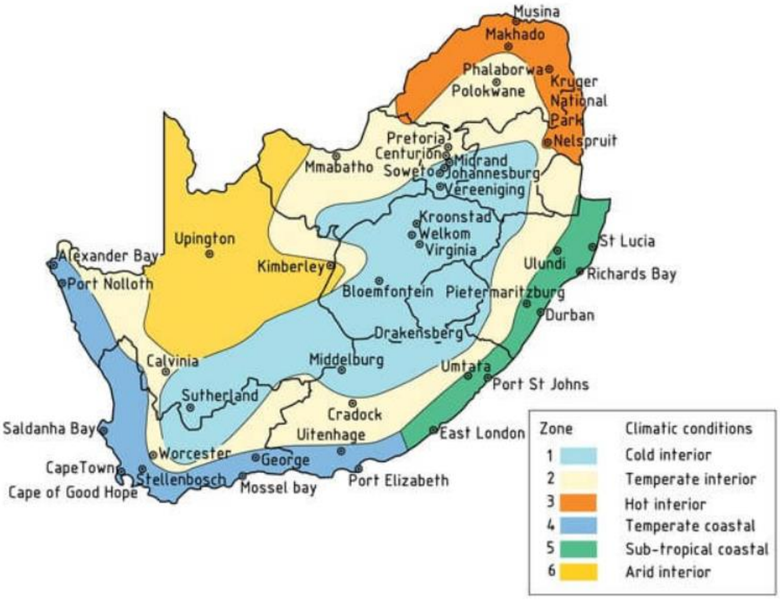

Figure 12: Climate zones of South Africa as per SANS 10400-XA: 2011. (SANS 10400-XA, 2011:15)

Step 2: Modelling and simulation of case study buildings

The next step in the process was to develop the IES_VE model required for the assessment of building performance for the existing case study office buildings in Johannesburg and Durban. Secondary data in the form of "as built" drawings were used to derive inputs into the simulation model. These inputs as shown in Figure 11 were the influencing factors of thermal mass performance. Through simulation, the buildings monthly heating and cooling energy loads were derived. The concrete thermal mass of the existing buildings, were modelled to match present conditions, and then adjusted in the IES_VE model from baseline heavyweight to lightweight concrete. For each simulation model the buildings monthly overall heating and cooling energy loads were recorded. The temperature to achieve thermal comfort within typical office buildings has been set at 22℃ (see Appendix A, Table 15). Using this temperature as a thermal comfort benchmark, the results of the optimum density of concrete thermal mass was evaluated for both buildings within their respective climatic regions.

Step 3: Analysis and interpretation of simulation results

From the simulation, a comparison assessment of the resultant heating and cooling energy loads were recorded for each thermal mass variation in the respective case study buildings. Three main scenarios were analysed. Firstly, the most favourable outcome in terms of the least energy required in MWh for heating from both concrete variations was compared and the influence of climate conditions recorded. Similarly, this assessment was carried out for the least energy required for cooling in MWh.

Step 4: Viability and feasibility appraisal of thermal mass adaptations.

The extent to which varying thermal mass would yield improvements in energy savings was then evaluated. A feasibility study was carried out to assess the cost savings from the energy savings achieved from thermal mass variations. A return on investment (ROI) was calculated as part of the feasibility study. The results from the investigation thus demonstrate the influence of thermal mass on reducing overall energy use within buildings, as well as cost and benefits from reduced electricity consumption for heating and cooling.

3.2 Primary and secondary data required and analysis process.

In order to conduct the study, a combination of primary and secondary data sets were collected and collated. Table 3 presents a summary of the primary and secondary data required to assist in response to the sub-questions outlined in Chapter 1. The relevant tools and processes needed to collect and analyse this data are summarised below.

Table 3: Summary of the primary and secondary data required to assist in response to the sub-questions

Sub Question 1 How do daily and seasonal temperature cycles influence thermal comfort within buildings and which passive energy interventions can be utilised for optimising thermal comfort under different climatic zones of South Africa?
Data required: Collection, Tools and Process The main source of data to collate daily and seasonal temperature cycles was through secondary data. Using the software programme, Climate Consultant (EnergyPlus), the regional macro-climate data for both Johannesburg and Durban were obtained and presented through graphs and psychrometric charts. EPW weather files were imported into the Climate Consultant software for both Johannesburg and Durban. The weather files were acquired from the International Weather for Energy Calculations (IWEC) data base that stores hourly weather statistics (ASHRAE, 2001) .Weather files were sourced from the Johannesburg and Durban (old international airport) weather stations.
Data Analysis Process Psychrometric charts for both Johannesburg and Durban were assessed on a seasonal basis to understand the temperature cycles. In addition to this, passive interventions which influence the contribution towards thermal comfort were highlighted and summarised. All graphical data are presented in appendices for reference and analysis and sub-findings are undertaken in Chapter 4.
Sub Question 2: Given structural performance priorities, what would be the responsive thermal mass variations for concrete in line with thermal comfort needs and temperature cycles for various climatic zones of South Africa?
Data required: Collection, Tools and Process The main source of data was secondary data. An overview of the influence of concrete as a thermal mass in different climate zones was reviewed, with consideration of its structural

strength. Research from publications (such as journals articles and text books as well as academic electronic references) was examined which investigated concrete as both a structural system and thermal mass.

Data Analysis Process

Research obtained on the dual role of concrete was highlighted in the literature review. Various types of thermal mass types have been categorised according to their structural performance versus their ability to perform as a thermal mass in different climate zones. The findings were tabulated, outlining the structural strength of concrete versus its thermal mass performance in different climate zones. Analysis and sub-findings specific to the case study buildings was undertaken in Chapter 5.

Sub Question 3:

What would be the overall optimal heating and cooling energy loads in MWh for building energy efficiency from thermal mass variations (lightweight concrete versus normal/heavyweight concrete) in different climatic zones of South Africa?

Data required: Collection, Tools and Process

The 'as built' drawings of existing office buildings in various climate regions under investigation were collected as primary data. These existing buildings were modelled on IES_VE software tool and the buildings monthly and annual heating and cooling energy loads (required to reach thermal comfort) were captured.

Data Analysis Process

An assessment on the influence of thermal mass was carried out by recalibrating the analysis based on the various concrete types investigated (heavyweight and lightweight). Within the IES_VE model, climate data and concrete density were interchangeable variables during the analysis process. After each simulation, heating and cooling energy loads were the resultant output. These results were graphically represented to highlight the favourable concrete type in relation to energy efficiency.

Sub Question 4: What would be the technical viability and economic feasibility of thermal mass variations in comparison to the energy savings arising from the energy efficiency gains across the various climate zones?
Data required: Collection, Tools and Process The heating and cooling energy loads were acquired from the IES_VE simulations conducted and were considered a primary data source. To calculate the economic feasibility of thermal mass adaptations, lightweight concrete and heavyweight concrete simulations were compared. Electricity costs were then sourced as secondary data to quantify the overall proposed energy savings from the difference in the cost required for heating and cooling loads.
Data Analysis Process A comparison of the buildings overall energy savings from optimising thermal mass was carried out, including a return on investment (ROI) feasibility study. Analysis and results are presented in Chapter 5.
Overall Research Question: How can the dual role of concrete elements as structural systems and thermal mass be adapted and optimised towards energy efficiency through passive cooling and heating for office buildings under different climatic zones of South Africa?
Data required: Collection, Tools and Process The data sourced and collected for each sub question was used to set up the basis for the proposed study.
Data Analysis Process By following the data analysis process for sub-questions 1-4, the overall research question was addressed.

3.3 Ethical Considerations

Due to the nature of this study the main ethical consideration was consent received for access and use of "as built" drawings for the case study buildings under investigation. This consent was provided by the building owners for the respective case study buildings. This information was used to build and simulate building models on IES_VE of the existing office buildings for further analysis.

Chapter 4: Site climate analysis of case study buildings.

4.1 Introduction

This chapter presents climatic data and analysis for the two case study office buildings in Johannesburg and Durban respectively. An analysis and summary of daily minimum and maximum temperature differences in each location and its relation to concrete thermal mass variations will be discussed. Furthermore, macro-climate and micro-climate analysis of the case study building sites are presented in relation to the influence of daily and seasonal temperatures on thermal comfort within the buildings. Both macro-climate and micro-climate have an important effect on both the energy performance and environmental performance of buildings.

Secondary data from 'as built' drawings indicate that buildings were designed using a mixed mode environmental control approach where both passive and active measures are applied for thermal comfort. The focus of the study is to find a means of optimising passive energy efficiency performance for indoor thermal comfort through the optimisation of thermal mass and the structural system. The subsequent reliance on HVAC systems (active measures) would be reduced, thus saving energy, and by extension, reduces building operational costs. The effects of lightweight and heavyweight concrete thermal mass are analysed with respect to internal thermal comfort of the two buildings. In order to analyse the internal thermal conditions, the macro-climate and micro-climate of the building location must be understood. Climate data was also utilised as secondary data for simulations of building energy loads for heating and cooling.

4.2 The Planes Building, Sandton, Johannesburg

The first case study building in Johannesburg is situated in the interior of South Africa located on a plateau at approximately 1700m above sea level. Altitude is therefore a key determinant of the city's climate. Figure 13 below shows an aerial view of the case study building. The climate is considered subtropical which means warm summers with late afternoon thundershowers and cool evenings. The winters are mild, with very low rainfall and relative humidity.

The Lodge, 38 Wierda Rd,
Wierda Valley West,
(Inanda Green Office Park)
Sandton,
Johannesburg,
South Africa
2196

Figure 13: Aerial view of "The Planes Building", Sandton, Johannesburg. (Source: Adapted from Google Maps)

The Planes Building is an existing two storey office building situated in the Inanda Green office park. Table 4 highlights the relevant features of this case study building.

Table 4: Relevant features of the Planes Building (Source: 'As built' drawings from building owners)

Building description	Two storey office building and carpark basement
Co-ordinates	26°06'48.0"S 28°03'18.5"E
Climate region (SANS 10400-XA:2011)	Cold interior (Highveld)
Altitude	±1700m ASL
Building occupancy	150 (average)
Gross floor area	2877m^2
Basement floor area	834m^2
Ground floor area	1074m^2
First Floor area	969m^2
Slope of roof	15°
Year of construction	1996

4.1.1 Macro-climate analysis of Johannesburg

Secondary data on macro-climate data for Johannesburg was sourced from Climate Consultant software, which is a component programme of EnergyPlus. The climate data were obtained from the IWEC data files. These 'typical' weather files are suitable for use with building energy simulation programs (ASHRAE, 2001). The monthly and annual climate data captured is considered very accurate since readings are recorded on an hourly basis. The reported data includes monthly mean averages of relative humidity, dew point temperatures, dry bulb temperatures, solar radiation and wind speeds. Subsequently, these raw data values were converted into graphs and psychrometric charts for analysis especially with regard to passive thermal control interventions. This software programme allows the user to set comfort zone temperature parameters and subsequently passive interventions for building design are considered. The default comfort zone temperatures have been set at a range between 20.5°C and 24°C degrees.

As shown on Graph 1B in Appendix B, the monthly maximum and minimum temperatures are highlighted for Johannesburg. As outlined in the literature study (Chapter 2), thermal mass works optimally in terms of indoor temperature regulation when there is a significant daily variation in temperature between the minimum and maximum average temperature. The data shows that the mean temperature difference between winter and summer months is approximately 10°C. The difference between maximum and minimum temperature during the summer months is approximately 15°C with an increase in the difference of temperature to approximately 20°C in winter. The annual mean dry bulb temperature experienced in Johannesburg is 16°C-19°C. These values are substantially close to the comfort zone range set between 20.5°C and 24°C. However, these temperatures do not include heat gain attained from solar radiation. In summer, cooling interventions would be required for indoor thermal comfort. The low mean dry-bulb temperature in winter (June, July) is approximately 10°C, which is significantly lower than the stipulated comfort zone. In order to accurately determine the climate conditions, factors such as solar radiation must be taken into consideration. Graph 2B builds on the information presented on Graph 1B as it incorporates the effects that solar radiation has to the overall temperature (dry-bulb and wet-bulb). Graph 2B indicates that during the summer seasons, the dry bulb temperatures rise beyond the comfort zone whereas during winter months the external temperatures just barely approach the comfort zone.

Graph 3B highlights the relationship between relative humidity and daily temperatures experienced throughout the year. Since warm air has the capacity to store more moisture than cold air, the overall relative humidity on a daily basis decreases as the temperature increases during the day and increases as the temperature decreases at night. In summer, the relative humidity experienced at night is approximately 80%, whereas during the day it averages at approximately 50%. In winter, the maximum relative humidity at night is approximately 60%, and averages at approximately 25% during the day. These fluctuations respond inversely to the dry-bulb temperatures. When comparing this on a seasonal basis, there is an overall higher relative humidity experienced during summer than in winter. This is due to the summer rain experienced in Johannesburg. From all the graphs presented, the four main environmental variables directly affecting thermal comfort are temperature, humidity, radiation and air movement. These four constituents of climate are important for the purpose of building design. Overall, Johannesburg can be classified as having a temperate (moderate) climate. There are seasonal variations between under heating and overheating, but neither is very severe.

4.1.2 Psychrometric charts – Johannesburg

Monthly psychrometric charts for Johannesburg are presented in Appendix B. Bearing in mind the temperature fluctuations, it is worthwhile to analyse the psychrometric chart on a seasonal basis. The psychrometric charts for December, January, February and March (summer approaching autumn) all show a significantly higher relative humidity than the rest of the year. This is mostly attributed to the fact that summer is the rainy season in Johannesburg. The high relative humidity can be decreased with the use of desiccants. However, in comparison to coastal areas, the severity of humidity in Johannesburg is negligible. During summer, the dry bulb temperatures range between 16°C to 27°C. Approximately 30% of the summer data points lie within the comfort zone. The rest of the data points are dispersed to the left and right of the comfort zone. This shows us that during summer, passive thermal controls can and should be used to achieve thermal comfort indoors at all times. The data points that fall to the right of the comfort zone (overheating period), would require a reduction in air temperature to reach comfort level. This can be passively achieved by increasing air flow through natural cross ventilation. The data points that fall to the left of the comfort zone will require an increase in air temperature to reach a comfort state. It should be noted that the incorporation of solar heat gains, internal heat gains from lighting, electrical equipment and occupancy gains would inherently passively heat the internal building environment. From the above information, the fluctuating daily to nightly temperatures experienced in Johannesburg would require high thermal mass materials such as concrete and brick that essentially absorb heat during the day and gradually releases it at night, therefore keeping the interior of buildings at a thermal level comfortable to its occupants.

A different pattern begins to emerge with the data points on the psychrometric charts from April to August as shown in Appendix B. The average temperatures and humidity slowly begin to reduce. During mid-winter, most of the data points fall to the left of the comfort zone, thus leaving the comfort zone empty. As a result, both heating and humidification would be required to reach a comfort state. Once again incorporating direct-passive solar systems that brings solar heat directly into a building would be beneficial. This can be fabricated through north-facing windows. Ideally, adjustable louvers on this face will allow for optimum comfort throughout the year. In addition to this, internal heat gains also play a significant role in passive methods to create warmth in a room. Lastly outdoor spaces will require wind protection if these spaces are to be comfortably used during the cold winter months. During the months preceding summer, the dry bulb temperatures begin to increase and move towards and into the comfort zone again and humidity increases, thus reducing the need to heat indoor spaces. In this case evaporative cooling methods should be considered to reach comfort levels. If buildings in Johannesburg were optimised with the above information in mind, passive control methods would be sufficient to aid in reaching indoor thermal comfort as weather fluctuations are not severe. However, the assistance of HVAC systems would still be necessary for fine tuning of controls.

4.1.3 Micro-climate analysis – Johannesburg case study

Eastern façade – The Planes, Sandton, Johannesburg

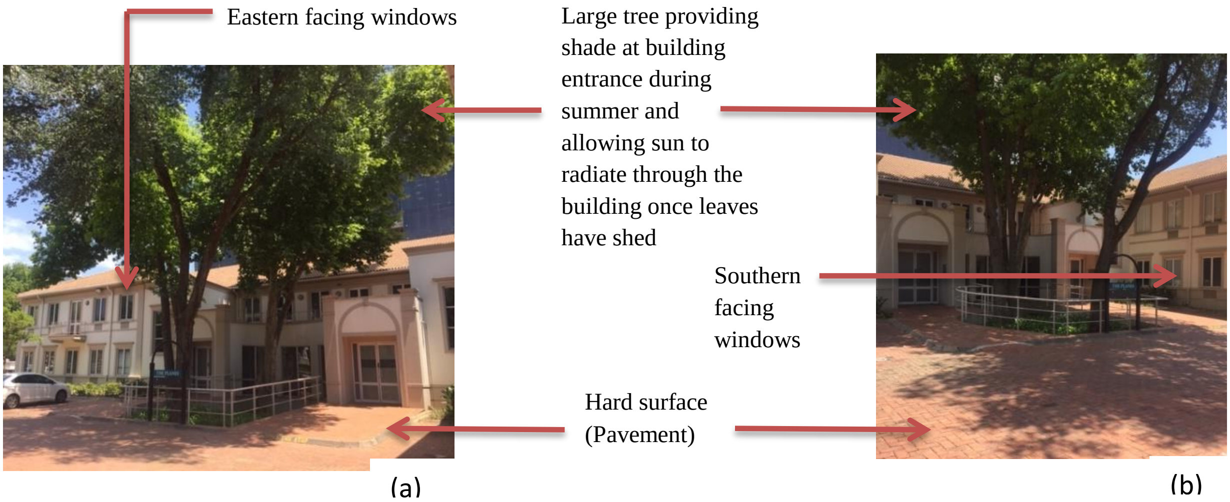

Figure 14: Building components on the eastern façade that influence the micro-climate.

Figure 14a and 14b, shows windows which occupy approximately 50% eastern façade. This allows morning light to radiate through into the building. However, the presence of the large tree in the foyer area casts shade over the entrance to the building. This in turn has a negative effect as it creates a dark, cold and uninviting entrance especially in winter. The rooms are facing the rising sun, and are likely to be warming during the early parts of the morning. However, as the day progresses, the midday sun may be slightly harsh in summer creating a heated area that exceeds comfortable room temperature even though in winter, these solar rays radiating through the windows could be welcome to counter low air temperatures.

Due to the ‘L’ shape of the building, there are southern facing windows present. This area of the office remains without sun throughout the year thus the building orientation could therefore have been configured differently to accommodate for solar radiation through these windows. There are no waterbodies in the vicinity of the building, but there are small plant beds along the entrance which may contribute towards evapotranspiration. Furthermore, pavement covers a relatively large portion around the entrance and extends into the visitors parking bays. This would cause over heating during summer months but provide a warm space during the cold winter mornings.

Northern façade – The Planes, Sandton, Johannesburg

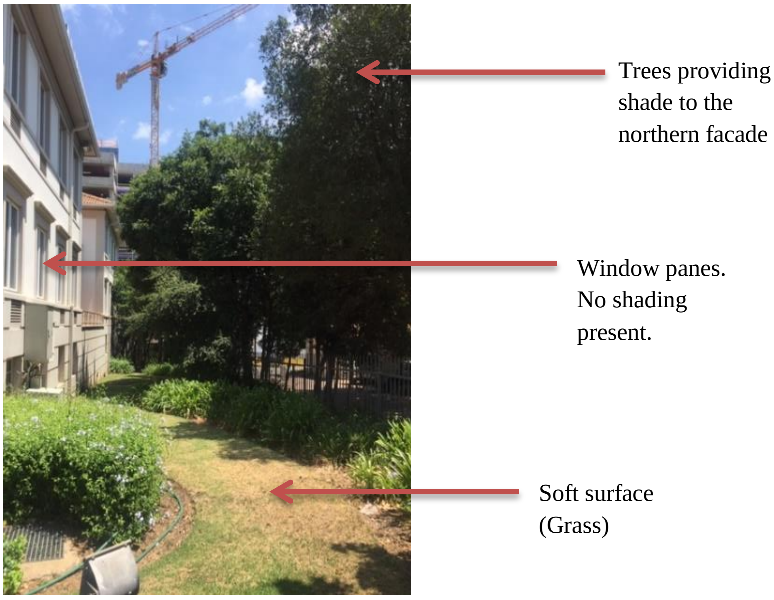

Figure 15: Building components on the northern façade that influence the micro-climate.

On the northern façade, the same window size is identified around the building. There are no signs of sun shading to prevent glare and heat from harsh north facing sun. This shows a lack a meticulous design with respect to passive design interventions for energy efficient buildings. However, good single glazed fixtures seal tightly. Overall the building has not been handled sensitively with respect to energy efficient design and interventions. Figure 15 shows the landscape of the site. The grass (soft surface) is closer to the building which can be identified as an efficient design of the landscape as the lush green garden will absorb heat instead of reflecting this onto the already heated northern façade. Trees are present along the northern garden, which provide some shade to the ground level of the building during midday hot summer months. However in winter, leaves will shed from the tress allowing sun rays to penetrate through the building.

Western façade – The Planes, Sandton, Johannesburg

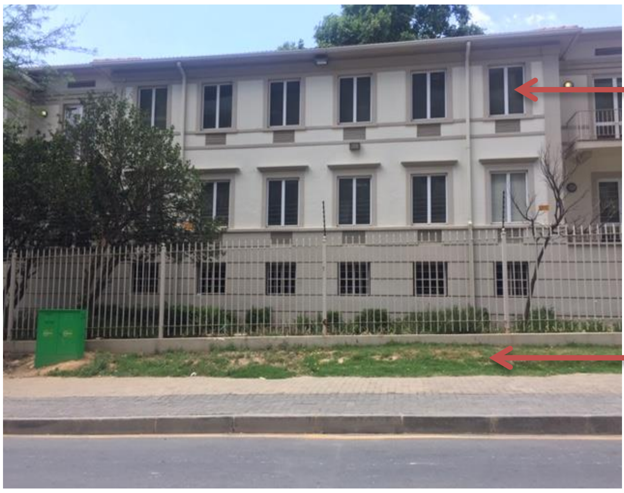

Figure 16: Building components on the western façade that influence the micro-climate.

The western façade is predominantly similar to the other facades with windows of the same size and evenly spaced as shown in Figure 16. The unshaded window means that there is direct solar radiation into the building through this façade in the afternoons, thus causing an increase in the internal building temperature. The western façade is considered warm during summer mornings and as the day progresses the increases in temperature and the sun path from east to west significantly warms this façade even further. However, in winter, the western facade is cold in the mornings and may require additional internal heating.

Southern façade – The Planes, Sandton, Johannesburg

Figure 17: Building components on the southern façade that influence the micro-climate.

Figure 17 shows the Southern façade which does not get much exposure to direct solar radiation as compared to the Northern façade and is therefore constantly shaded due to the direction of the sun path. The area serves as an entrance to the basement parkade. The hard surface paving adjacent to the building heats up during the mid to late afternoon and facilitates an external to internal heat transfer through the building envelope during the day. Even though the extent of heating on this facade is not as prominent as the Northern façade, thermal mass is still able to absorb heat from adjacent paving. The ability of thermal mass to store heat can assist with cool internal temperatures in summer, but could result in below comfort temperatures during winter.

4.1.4 Thermal control strategy for the Planes Building under investigation.

From the climate analysis carried out, it is evident that the climate in Johannesburg is relatively mild, with mean annual outdoor temperatures ranging between 10°C-20°C (excludes internal gains from occupants, lighting and equipment). This suggests that constant air conditioning may not be a requirement if passive interventions are considered early enough and implemented at the design stage. In saying this, active interventions would still be a requirement for temperatures falling below and above the mean temperature range. For example, there are days during winter that can be uncomfortably cold and mechanical heating is likely a requirement. Similarly, mid-summer days can be scorching hot, and when considering internal heat gains with hot climatic conditions, this may result in considerable internal cooling required which would necessitate occupational air conditioning. From a retrofitting perspective, there are certain passive interventions that could reduce the overall heating and cooling loads for the building. These include the addition of sun shading to the northern facade as well as improved landscaping and trees to the eastern gardens (outdoor spaces). Thermal mass alternatives for reducing the building's operational energy are presented and analysed further in the next chapter.

4.2 Frosterley Crescent, Umhlanga, Durban

4.2.1 Macro-climate analysis of Durban

The second case study building is situated in the Umhlanga business district, within the city of Durban, on the eastern coast of South Africa. Durban has a warm, subtropical climate, and the air is heavy with humidity. In winter, the climate is mild to warm, with very low rainfall. However due to large altitude variations, some western suburbs are moderately cold in winter. The metropolitan area is topographically hilly, except in the immediate vicinity of the central business district and the harbour which is relatively flat. Figure 18 shows an aerial view of the building.

Frosterley Crescent
Business and Commercial
Park
4 Frosterley Crescent
Umhlanga
Durban
South Africa
4051

Figure 18: Aerial view of "Frosterley Crescent", Umhlanga, Durban (Source: Adapted from Google Maps)

The building, situated at 4 Frosterley Crescent in Umhlanga is an existing two storey office building with a basement carpark beneath ground level. Table 5 highlights some the relevant features of the building.

Table 5: Relevant features of Frosterley Crescent Building (Source: 'As built' drawings from building owners)

Building description	Two storey office building and carpark basement
Co-ordinates	29°44'03.9"S 31°03'53.6"E
Climate region (SANS 10400-XA, 2011)	Sub-tropical Coastal
Altitude	±200m ASL
Building occupancy	250 (average)
Gross floor area	5317m^2
Basement floor area	2046m^2
Ground floor area	1701m^2
First Floor area	1570m^2
Slope of roof	15°

4.2.2 Macro-climate analysis - Durban

Similar to the climate data for Johannesburg, macro-climate data were sourced from Climate Consultant software tool. The climate data are presented and discussed further in the following sub-sections.

The data are analysed in detail and interpreted through graphs and psychrometric charts as presented in Appendix C. Similar to the Johannesburg case study, a comfort zone has been set on the software program and passive interventions for building design are proposed. The generic comfort zone temperatures have been set at a range of between 20.5°C and 24°C. From Graph 1C in Appendix C, the maximum and minimum monthly temperatures for Durban are highlighted. Results show the mean temperature difference between winter and summer seasons to be approximately 6-7°C, thus illustrating a fairly consistent mean temperature profile throughout the year. However, if focus is cast on the overall maximum and minimum temperature range per month a significant difference is noticed. During the months of October to March, each month had a difference in temperature of approximately 15°C, whereas during peak winter months the max to min temperature is approximately in the range of 20-25°C. Even though the mean temperatures are consistent over the year, the difference between the monthly minimum and maximum temperatures are significant. It must also be noted that as air temperature decrease, the relative humidity increases and vice versa, which may explain why people describe the climate as consistently hot, when it is known that there are significant temperature fluctuations.

In order to accurately factor in climatic conditions more holistically, influences such as solar radiation must be taken into consideration. Graph 2C builds on the information presented in Graph 1C as it incorporates the effects that solar radiation has on the overall temperature (dry-bulb and wet-bulb). From Graph 2C, it is evident that during the summer seasons the dry bulb temperatures rise beyond the comfort zone, whereas during winter months temperatures consistently approach the comfort zone.

Graph 3C highlights the relationship between relative humidity and daily temperatures experienced throughout the year. In summer, the relative humidity experienced during the night is approximately 97% whereas during the day it averages around 62%. In winter, the maximum relative humidity at night is approximately 97%, and averages around 45% during the day. These fluctuations respond inversely to the dry-bulb temperatures. From the humidity levels, it is clear that Durban experiences very high humidity throughout the year which may induce a feeling that it is hotter than it actually is. During summer, humidity remains high during the night and day (above 60%). During winter the fluctuations in humidity increase, but overall humidity remains high.

It is clear in the case of Durban that the four main environmental variables directly affecting thermal comfort are temperature, humidity, radiation and air movement. While the temperatures seem to fall directly within the comfort zone, factoring high humidity makes the overall climatic conditions seem as if it is exceeding the specified comfort zone. As a result, Durban can be classified as having a moderate sub-tropical climate with average minimum and maximum temperature fluctuations and moderate-to-high humidity.

4.2.3 Psychrometric charts – Durban

Psychrometric chart are analysed on a monthly/seasonal basis. The psychrometric charts (see Appendix C) for December, January, February and March (summer approaching autumn) all show high levels of relative humidity because it is also the rainy season. However, the humidity remains relatively constant through the year with slightly lower levels in winter. These year-round humidity values can be attributed to the fact that Durban is a coastal city, therefore the warm Indian Ocean air significantly contributes to the severely humid conditions. The high humidity can be reduced with the use of desiccants.

Annual dry bulb temperatures range between 16°C to 30°C, and between November and April there are very few data points that fall within the comfort zone (majority of the data points fall above and to the right of the comfort zone). This indicates very high humidity as well as high dry and wet bulb temperatures. Passive temperature controls during summer could be used to achieve thermal comfort at all times. Given that data points to the right of the comfort zone would require a reduction in the air temperature to reach comfort level, this can be achieved passively by increasing air flow through natural cross ventilation (however, due to the high humidity this might not be as effective as in Johannesburg), or the implementation of sun shading. Mechanical interventions such as fan-forced ventilation or conventional air-conditioning systems could be required to reduce the effects of overheating. A combination of cooling and dehumidification interventions would be necessary in order to achieve the stipulated comfort zone.

The data points that fall to the left of the comfort zone, would require an increase in air temperature in order to reach a comfort state. In addition, Durban is characterised by fluctuating day to night temperatures. However, the high humidity plays a significant role in stabilising these fluctuations, thus leaving the thermal experience as constantly hot. Interpretation of the psychrometric chart suggests that thermal mass can also be used as a passive means to absorb heat during the day and gradually releases it at night. This is contradictory to the initial assumptions where, heavier thermal mass would be deemed not to perform effectively in terms of energy efficiency under high temperatures and high humidity in Durban.

From May to August, average temperatures slowly begin to reduce and the relative humidity reduces slightly. During mid-winter, approximately 40% of the data points fall within the comfort zone, while the rest of the points fall out of the comfort zone (dispersed to the left and the right, with most of them to the left). Mechanical means of heating is also not required in winter as sufficient heat can be acquired from internal gains and solar gains. Sun shading should be utilised when temperatures exceed comfort zone temperatures in winter. During the months approaching summer, the dry bulb temperatures begin to increase and move away from the comfort zone again, thus requiring further cooling interventions.

In the case of hot climates and high humidity, various dehumidifying techniques should be used to reduce the dampness in the air. With the increase in humidity the temperature difference between the outside and inside of the building decreases, making it more difficult for passive cooling interventions to work effectively. Dehumidifying strategies should therefore be used. These strategies include natural ventilation when the outside moisture in the air is lower than the inside, running a fan to increase speed in airflow, placing containers of desiccant in the building and as a last resort, using an air-conditioning system. If buildings in Durban are designed with the above strategies in mind, passive control methods can facilitate a building to reach comfort levels for most of the year, while conventional air conditioning is reserved for the rare periods of excessively hot and humid conditions.

4.2.4 Micro-climate analysis – Durban

Eastern Façade – Frosterley Crescent, Umhlanga, Durban.

Figure 19: Building components on the eastern façade that influence the micro climate.

As shown in Figure 19, the windows are evenly spaced on ground and first floor levels. This allows morning light to radiate through into the building. There is a presence of vegetation in the form of trees adjacent to the foyer area. However, the trees do not provide significant shade. The foyer area remains warm and inviting from morning to mid-afternoon as rooms are facing the rising sun. However, as the day progresses, the midday sun may be slightly harsh in summer creating a heated area that exceeds comfort levels.

There are no signs of sun shading to prevent glare and heat from harsh sun. This shows a lack of meticulous building design with respect to passive design interventions for energy efficiency. In winter, these solar rays radiating through the windows would be welcome to counter the low indoor temperatures. One of the most dominant features is the mass of paving that surrounds the building. The paving covers a relatively large portion from the entrance and extends to the visitors parking bays. This would cause overheating, both in summer and winter, primarily due to the hot and humid climate throughout the year.

Northern façade – Frosterley Crescent, Umhlanga, Durban.

Figure 20: Building components on the northern façade that influence the micro climate.

On the northern façade, window profiles similar to the eastern façade are identified with tightly sealed, single glazing fixture. Figure 20 shows the landscape adjacent to this façade. The grass (soft surface) and vegetation is found to be closer to the building which can be identified as an efficient design of the landscape as the lush green garden would moderate heat instead of reflecting this onto the already heated northern façade. Trees are adjacent to this façade which provides some shade to the building during midday hot summer months. In addition, there is a waterbody adjacent to this face of the building which may be counterintuitive to the energy efficiency of the building. Since outside air is already highly saturated with water molecules (high humidity), evapotranspiration may contribute towards an even higher humidity surrounding the building.

Western façade – Frosterley Crescent, Umhlanga, Durban.

Reduced number of window panes with less solar radiation penetrating through this facade

Figure 21: Building components on the western façade that influence the micro-climate

The western façade is unlike the other facades with windows being the same size and evenly spaced. As shown in Figure 21, the ablution facilities are located on this face with a reduced number of windows which means reduced external to internal solar heat transfer within the building. The western façade is considered favourable for summer conditions as it remains cool for most of the morning and early afternoon as it does not receive direct sunlight. However, in the late afternoon the presence of the sunlight warms this face of the building. If thermal mass is adequately optimised, the additional heat load can be absorbed, stored and then dissipated later in the night.

Southern façade – Frosterley Crescent, Umhlanga, Durban.

Tightly sealed window panes with no solar radiation penetrating through this facade

Hard surface (pavement)

Figure 22: Building components on the southern façade that influence the micro-climate.

The Southern façade (see Figure 22) is not exposed to direct sunlight and is constantly shaded. The hard surface paving adjacent to the building heats up during the mid to late afternoon and facilitates heat transfer into the building. This facade does not experience direct sunlight and remains cool relative to all other building facades.

4.2.5 Thermal control strategy for Frosterley Crescent building.

The results of the climate analysis demonstrate that Durban's climate is characterised by significant change in minimum and maximum daily temperatures, even the high humidity moderates this variation. The humidity falls between the range of 60%-100% and an annual mean temperature of 17°C -25°C (excluding internal gains within buildings), constant air conditioning could therefore be required even after optimising passive energy interventions. During winter, indoor thermal conditions may be within the comfort zone, but during summer, cooling load would necessitate the use of air conditioning. Internal thermal conditions during winter may be comfortable, however during summer cooling loads would definitely be required. There are certain passive interventions that can be implemented on the building to reduce the overall energy loads used for heating and cooling. These include the addition of sun shading to the northern façade and adjustable louvres, the inclusion of soft landscaping and trees to grounds adjacent to the eastern façade and the overall reduction of hard surfaces. Thermal mass alternatives for reducing operational energy are investigated further in the next chapter.

Chapter 5: Energy performance modelling and simulation – Analysis and findings.

5.1 Introduction

This chapter presents the analysis on building modelling and simulation for energy performance in order to derive the key findings of the study. The case study buildings were modelled using the Integrated Environmental Solution Virtual Environment (IES_VE) for energy simulation. The software was purposefully applied to derive the heating and cooling loads for each building. Various factors of each building (such as orientation, utilisation and occupancy) were considered in the derivation of internal heating and cooling requirements to maintain a consistent temperature of 22°C (with set points fixed at 21°C and 23°C under the heating and cooling operation profiles respectively) during working hours,6:30am to 6:30pm, Monday to Friday. The building models for the simulation were aimed at facilitating comparison on the effects of heavyweight versus lightweight concrete as thermal mass in relation to thermal comfort and energy consumption.

Initially, an overview of the background and assumptions used within the IES_VE software analysis tool is described, followed by the heating and cooling energy load results of each case study building and the related analysis. In addition, a feasibility assessment was carried out to quantify the overall energy cost savings achieved from thermal mass adaptations in the respective climate zones. This allowed for the derivation of thermal mass adaptations.

5.2 Background and understanding of analysis software IES_VE.

The investigation of a building's energy performance involves the analysis of three modes of external to internal heat transfer, which include; conduction, convection and radiation. As discussed in section 2.2, these modes are influenced by a number of factors such as building envelope, building orientation, occupation, indoor internal heat gains and natural ventilation. The heat balance method (see Figure 2) was used to derive the heating and cooling energy loads required for indoor thermal comfort. IES_VE building energy performance analysis software was employed to model and analyse the case study buildings in Johannesburg and Durban, identified in Chapter 4. IES_VE is a calibrated simulation software program that has Agrement South Africa certification for SANS10400-XA compliance.

The IES_VE building energy performance software analysis programme, used the Apache loads calculation engine to derive cooling and heating energy loads based on the ASHRAE heat balance method (Splitler, 2014). The assessment based on the simulations assisted in finding opportunities for design optimisation. The analysis of the simulated heating and cooling loads for lightweight and heavyweight concrete within a two story office building in two different climatic regions was then followed by a feasibility study of the thermal mass adaptations. Analysis of both case study buildings were evaluated before HVAC sizing was specified.

5.3 Baseline inputs and assumptions into IES model.

As part of secondary data, the geographical location, co-ordinates, elevation, building orientation and climate details were acquired for each building. These details were presented in Chapter 4. The programme applied the data to search for the weather files to be incorporated as an input process of the simulation. As highlighted in Chapter 3,these weather files were obtained from the ASHRAE data base. (ASHRAE,2001)

Layouts of the existing building (in Autocad format) were sourced from building owner's records. The plans were used to model an outline of the building structure to include construction components such as floor surfaces, walls, glazing and fenestrations, ceilings and roofs (see Appendix D for overall plans). Once individual room areas of the building plan were obtained, specific properties of the construction components were specified as part of the process of defining building envelopes which were then applied to each room template. Composition of these building envelopes included the material composition of various layers (structural elements, insulation and finishes). The programme then derived the overall thermal conductivity of each building envelope unit which incorporated it into final calculations towards finding the required heating and cooling loads. This was applied to all walls (external and internal), floors and the roof of both case study buildings.

From the literature reviewed in section 2.5, the standard strength recommended for reinforced structural concrete is 25MPa. Standard mix concrete with 19mm aggregate has a density of approximately 2400kg/m^3 which was applied as the baseline case into simulations. Lightweight concrete, achieving a similar strength was included in simulations. SANS 794:2009 and SANS 5862-1:2006 outline low density aggregates commonly used in construction which include; foliated vermiculite, perlite, loamed slag, natural pumice, scoria and expanded clay, shale or slag (SANS 794:2009) and (SANS 5862-1:2006). These low density aggregates can be used to form lightweight concrete mixes with appropriate strength and workability. As highlighted in section 2.5, lightweight concrete made from natural aggregates, with a density of 1200kg/m^3, results in an approximate lightweight concrete strength of 25MPa.

The table below highlights four IES_VE models created and the main corresponding building material properties used to model each case study office building. The main building skeleton for both case studies (ascertained from AutoCAD building layouts) were similar with a double skin brick wall forming the building exterior, a concrete surface bed at the basement level and reinforced concrete slabs on ground and first floor respectively. Although different in size, both buildings contained single glazed windows with aluminium framing as well as slate tiled roofs. IES_VE programme provides the U-values and thermal mass values for specified building components selected. Building parameters for Model 1A and Model 2A were considered as baseline models for Johannesburg and Durban case studies, which exhibited existing conditions with heavyweight concrete at a density of 2400kg/m^3. Model 1B and 2B are the models that assessed lightweight concrete for both case study buildings at a density of 1200kg/m^3. Analysis of the output results for each model will be discussed further in the next section.

Table 6: Building material properties for case study buildings in Johannesburg and Durban (Adapted from building owners drawing records and IES_VE material properties).

			Model 1A *Johannesburg heavyweight concrete construction* **Model 2A** *Durban heavyweight concrete construction*		**Model 1B** *Johannesburg lightweight concrete construction* **Model 2B** *Durban lightweight concrete construction*	
Major building components and assemblies applied to the IES model	**Case study building composition**	**Thickness (m)**	**U – value (W/m^2K)**	**Thermal mass ($kJ/(m^{-2}K)$)**	**U – value (W/m^2K)**	**Thermal mass ($kJ/(m^{-2}K)$)**
Internal floor	1. Synthetic carpet 2. Screed 3. Reinforced concrete slab	0.255	1.75	240	0.99	120
Outer wall compositions (inside to outside)	1. Gypsum plastering 2. Double skin brick wall 3. Gypsum plastering	0.250	2.04	133	2.04	133
Internal partition	1. Plasterboard 2. Cavity 3. Plasterboard	0.075	1.79	8.75	1.79	8.75
Surface bed	1. Cast concrete 2. Felt and membrane	0.155	2.91	156	1.58	96.38
Roof Assembly	1. Slate tiles 2. Timber Board 3. Polyurethane Board	0.445	0.0973	0	0.0973	0
Fenestrations	1. Outer pane	0.01	1.6	0	1.6	0

The next step was to consider the critical internal heat gains in the building. For both case study buildings, internal heat gains primarily came from florescent lighting, electronic loads from office computers and equipment and occupancy (the users) of the building. Daily profiles were set up in terms of allocated times when occupancy /internal gains were most likely to occur. These profiles were set for Monday to Friday from 6:30am to 6:30pm (typical office hours), with "no occupancy" assumed on weekends. As both case study buildings were two storey office buildings with similar parameters, the same internal gains per m^2 were applied to both buildings, which included lighting loads at $10W/m^2$, and office computer and equipment loads at $15W/m^2$ (Arnold, 2007). As highlighted in Chapter 4, occupancy patterns were considered when carrying out the thermal simulations. The programme also incorporated air exchanges in which case the natural ventilation maximum flow rate was set to be 10l/s/person (Parker, 2013). The design was based on space conditioning where the applied set point temperature was fixed at 21°C and 23°C under the heating and cooling operation profiles respectively. Table 7 shows a summary of input internal heat gains used for energy efficiency simulations.

Table 7: Internal heat gains for case study buildings in Johannesburg and Durban (Arnold, 2007) and (Parker, 2013).

Internal heat gains in the case study buildings	**Model 1A** *Johannesburg heavyweight concrete construction* **Model 1B** *Johannesburg lightweight concrete construction*	**Model 2A** *Durban heavyweight concrete construction* **Model 2B** *Durban lightweight concrete construction*
Occupancy	150 persons	250 persons
Lighting loads	10W/m^2	10W/m^2
Office computer and equipment loads	15W/m^2	15W/m^2
Natural ventilation maximum flow rate	10ℓ/s/person	10ℓ/s/person

5.4 The Planes Building, Johannesburg _ Model 1A and Model 2A

The extracts below (see Figure 23) shows the IES_VE Model 1A/2A created for the Planes Building situated in Johannesburg. Each room has been individually modelled with specific properties to simulate existing site conditions.

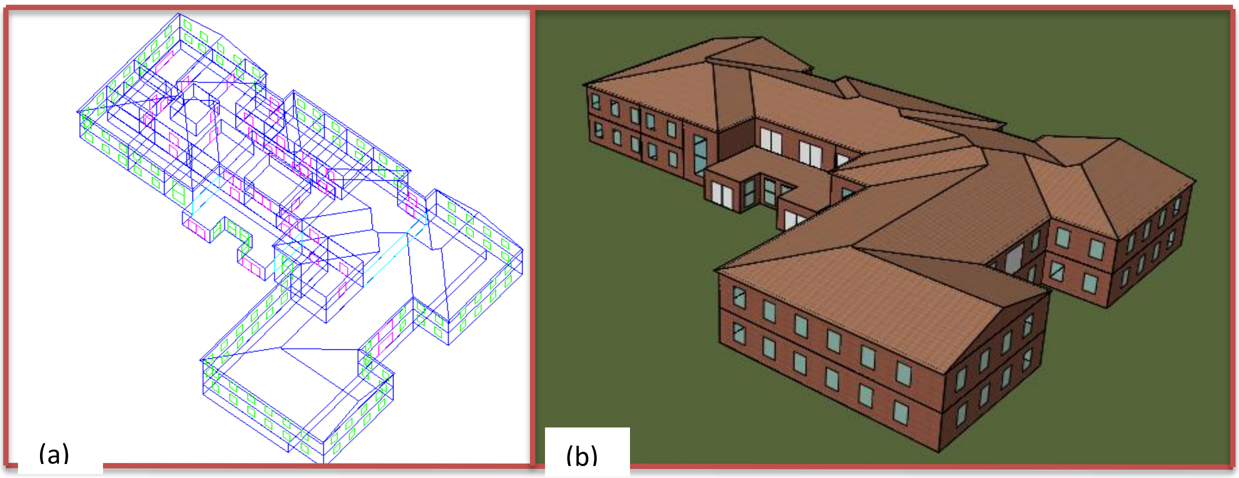

Figure 23: The Planes Building complete model in (a) frame and (b) rendered views

Within Model 1A, the structure of the building was created and analysed as a baseline case with heavyweight concrete surface bed and reinforced concrete slabs components. Model 2A was subsequently created with lightweight concrete replacing the heavyweight concrete. In order to understand and quantify the effects of low density concrete, all other construction types including building elements, materials, and material properties remained the same, such that the type of concrete used was the variable under investigation. After analysing both simulations based on the heat balance method, the program derived sensible cooling and heating loads as summarised in the next section.

5.4.1 Energy performance analysis and results:

Heating Plant Sensible Loads

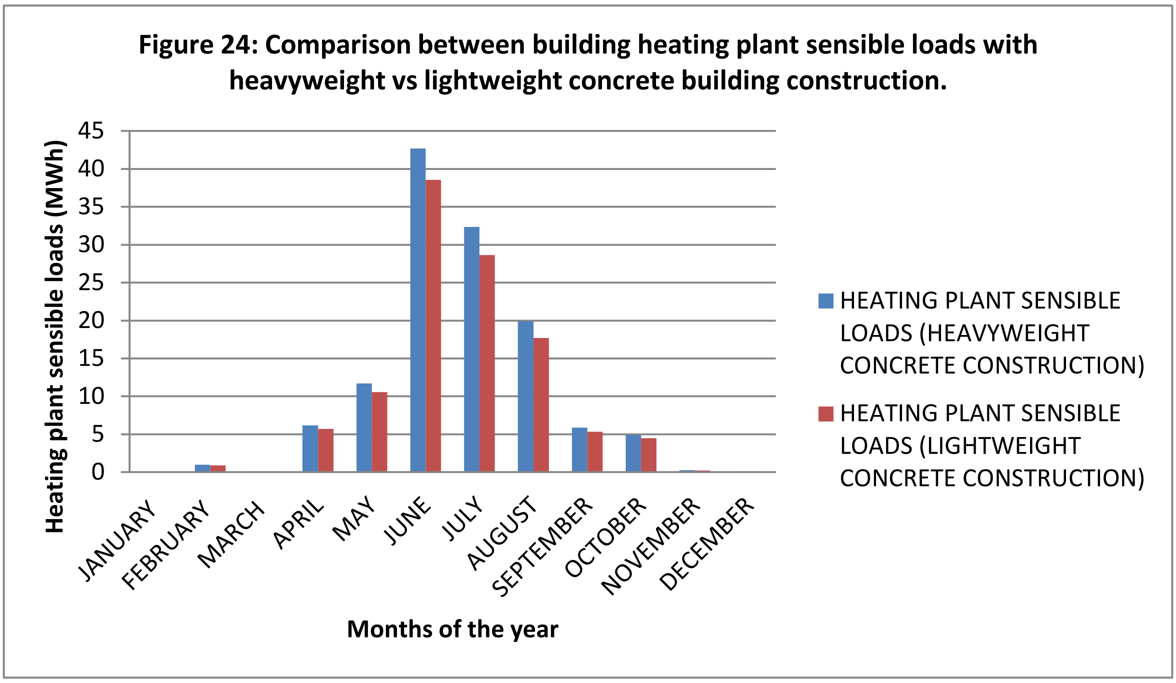

Figure 24: Comparison between heating plant sensible loads with heavyweight vs lightweight concrete.

Figure 24 indicates the heat required to keep internal office temperature consistent at 22°C. The heat required was measured in MWh for each month of the year. The results show that most heat was required during the winter months of June, followed by July and August respectively. On the other hand, heating was barely required (during office hours) between the months of November and March. Interestingly, the building model analysed with lightweight concrete seemed to be the favourable concrete construction type for heating loads required within the office space.

Table 8 highlights the savings in heating load (MWh) as well as a percentage difference acquired between lightweight and heavyweight concrete construction throughout the year.

Table 8: Total annual heating energy loads and potential energy savings/losses acquired from the difference between lightweight and heavyweight concrete construction.

	Model 1A (Baseline)	**Model 1B**		
	Heavyweight concrete construction (MWh)	**Lightweight concrete construction (MWh)**	**Total monthly savings MWh)**	
January	0,00	0,00	0,00	
February	0,99	0,89	0,10	
March	0,11	0,09	0,02	
April	6,19	5,73	0,46	
May	11,70	10,58	1,12	
June	42,70	38,56	4,14	
July	32,33	28,65	3,68	
August	19,90	17,71	2,19	
September	5,88	5,33	0,55	
October	4,91	4,51	0,40	
November	0,27	0,24	0,03	
December	0,10	0,08	0,02	
Total annual heating load required (MWh)	125,08	112,37	**12,71**	**Total annual energy load difference (MWh)**

The total heating load utilised over one year for heavyweight concrete construction amounted to 125,08MWh versus the total heating load for lightweight concrete construction which equated to 112.368MWh. A total energy savings of 12.71MWh was attained from the utilisation of lightweight concrete over heavyweight concrete for this site.

Cooling Plant Sensible Loads

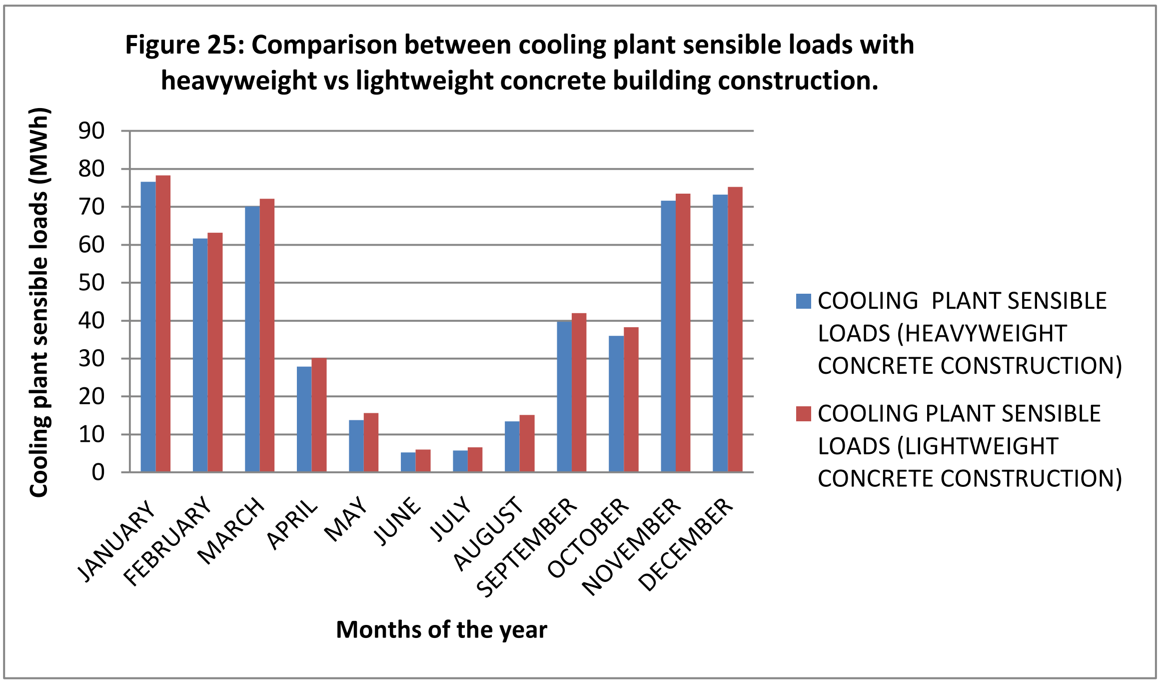

Figure 25: Comparison between cooling plant sensible loads with heavyweight vs lightweight concrete building construction.

Figure 25 indicates the energy required per month to remove excessive heat from the internal office environment to achieve thermal comfort at 22°C. It is clear both active and passive interventions would be required to cool the internal office space throughout the year. During summer, more energy is required for cooling with values reaching above 70MWh in November, December and January. In contrast to the heating load, heavyweight concrete construction is shown to be more favourable compared to lightweight concrete construction in terms of energy savings required for cooling. Lightweight concrete construction consistently requires more energy to cool a space throughout the year for this specific site in Johannesburg. The difference in MWh between heavyweight and lightweight concrete construction is highlighted in the Table 9.

Table 9: Total annual cooling energy loads and energy savings/losses acquired from the difference between lightweight and heavyweight concrete construction.

	Model 1A (Baseline)	Model 1B		
	Heavyweight concrete construction (MWh)	**Lightweight concrete construction (MWh)**	**Total energy difference MWh)**	
January	76,63	78,33	-1,70	
February	61,68	63,19	-1,50	
March	70,10	72,17	-2,07	
April	27,86	30,13	-2,27	
May	13,82	15,68	-1,86	
June	5,26	6,00	-0,73	
July	5,78	6,64	-0,86	
August	13,43	15,15	-1,72	
September	39,69	41,95	-2,26	
October	35,95	38,31	-2,35	
November	71,61	73,51	-1,90	
December	73,19	75,28	-2,09	
Total annual cooling load required (MWh)	495,01	516,33	-21,32	**Total annual energy load difference (MWh)**

The total cooling load utilised over a year for heavyweight concrete construction amounted to 495MWh, while the total cooling load for lightweight concrete construction equated to 516MWh. This is significantly greater than the heating loads required which related directly to the climate and occupancy hours of the office building (6:30am to 6:30pm). Considering heavyweight concrete as the baseline model, it is evident that this was the favourable construction type compared to the lightweight concrete option, as less cooling load is required to obtain a constant internal temperature. Lightweight concrete construction for this particular case study resulted in an extra annual energy load of 21.3MWh. This amounted to 4% of additional annual energy required compared to the baseline heavyweight concrete option.

Accumulated heating and cooling energy loads.

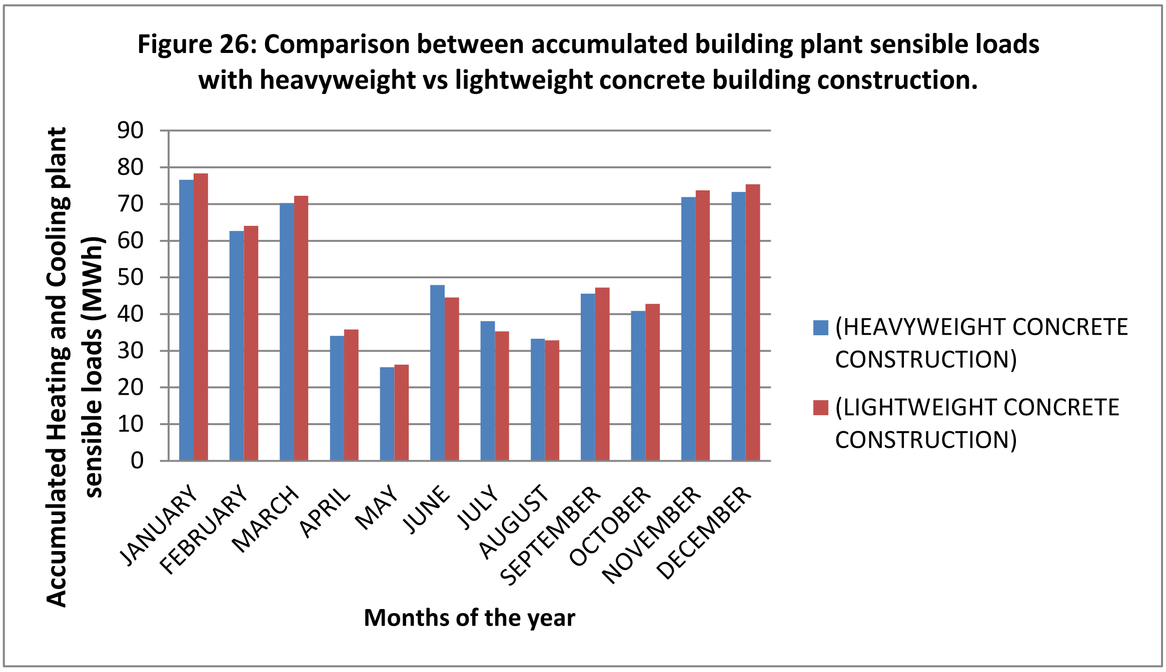

Figure 26: Comparison between building plant sensible loads with heavyweight vs lightweight concrete building construction.

Figure 26 shows the accumulated heating and cooling energy loads required to obtain an internal consistent temperature of 22°C within the case study office building under investigation. It is evident from the results that during Autumn, Spring and Summer seasons (September to May) in Johannesburg, heavyweight concrete was the favourable form of construction material compared to lightweight concrete in terms of efficiently utilising thermal mass to aid in internal building temperature regulation.

Table 10 below considers the most favourable annual cooling and heating loads between either heavyweight or lightweight concrete construction and determines the percentage of energy load attributed to heavyweight and lightweight concrete construction.

Table 10: Total annual energy loads showing the least energy required for heating and cooling between heavyweight and lightweight concrete construction.

	Least energy required per month for heating and cooling loads (MWh)	**Favourable concrete type (Heavyweight /Lightweight)**	**Percentage of energy load required per month (%)**	**Percentage of energy load required per month due to heavyweight concrete construction (%)**	**Percentage of energy load required per month due to lightweight concrete construction (%)**
JANUARY	76,63	Heavyweight	12,49	12,49	-
FEBRUARY	62,68	Heavyweight	10,22	10,22	-
MARCH	70,21	Heavyweight	11,45	11,45	-
APRIL	34,05	Heavyweight	5,55	5,55	-
MAY	25,52	Heavyweight	4,16	4,16	-
JUNE	44,56	Lightweight	7,26	-	7,26
JULY	35,29	Lightweight	5,75	-	5,75
AUGUST	32,86	Lightweight	5,36	-	5,36
SEPTEMBER	45,57	Heavyweight	7,43	7,43	-
OCTOBER	40,86	Heavyweight	6,66	6,66	-
NOVEMBER	71,88	Heavyweight	11,72	11,72	-
DECEMBER	73,29	Heavyweight	11,95	11,95	-
TOTAL	**613,40**		100,00	81,63	18,37

From the analysis of energy performance of the Planes Building (under both heavyweight and lightweight concrete construction), it is evident that during peak winter months (June, July and August), lightweight concrete was favourable amounting to 18.37% of total annual energy loads required. On the other hand, heavyweight concrete was the favourable option for the rest of the year and accounting for 81.63% of the total annual energy loads required.

5.5 Feasibility study

Table 11: Energy cost savings / loss due to the implementation of lightweight concrete in relation to baseline heavyweight concrete

The Planes Building - Johannesburg			
Passive energy intervention due to thermal mass			
	Total accumulated energy loads required (kWh)	**Cost / kWh**	**Derived total cost (R)**
Total energy required with heavyweight concrete construction. (Baseline scenario)	620000,00	1,26	R 781 200,00
Total energy required with lightweight concrete intervention.	629000,00	1,26	R 792 540,00
Difference in energy required per year (saving / loss)	-9000,00		**-R 11 340,00**
			Loss
Estimated cost of concrete / m3	**Total Volume (m3)**	**Cost / m3**	**Total cost**
Surface bed + internal concrete slabs (Heavyweight)	650,30	R 1 242,22	R 807 815,67
Surface bed + internal concrete slabs (Lightweight)	650,30	R 3 872,22	R 2 518 104,67
Difference in construction costs between lightweight and heavyweight concrete for this case study			**R 1 710 289,00**
Payback period - return on investment	**Total cost**		
Total cost of lightweight concrete intervention	R 2 518 104,67		
Energy cost savings/loss per working day	**-R 43,62**	Loss	
Pay back period	No pay back period as a loss of R43,62 is being accumulated each working day.		
Limited period of return on investment:	N/A as cost of lightweight concrete construction is greater than baselin heavyweight concrete construction.		

The economic feasibility and potential energy cost savings from implementing lightweight concrete as opposed to heavyweight concrete in building construction is indicated in Table 11.

Firstly the total accumulated annual energy loads were quantified as costs. Since lightweight concrete construction required more energy to heat and cool the Planes office building, the estimated cost difference in the cost of energy between heavyweight and lightweight concrete amounted to R11340. In addition, according to quotes received from the building materials company, Lafarge Holcim Ltd (Durban branch), lightweight, natural aggregate concrete with a density of approximately 1200kg/m^3 costs R3872.22 per cubic meter. Whereas, a standard 25MPa, 2400kg/m^3 heavyweight concrete option is priced at R1242.22 per cubic meter.

Delivery costs were included in these quotes at an estimated travel distance of 15km. It is for these reasons that there is no payback period as a loss of R43,62 has been calculated per working day in addition to the extra initial R1 710 289 cost of the specialised lightweight concrete. Therefore it is not feasible to implement lightweight concrete. Baseline heavyweight concrete is to remain, as it is more feasible.

5.6 Frosterley Crescent, Durban_ Model 2A and Model 2B

Figures 27(a) and 27(b) show the IES_VE Model 2A/2B created for the Frosterley Crescent Building in Durban. Each room has been individually modelled with specific properties for the simulation of 'as built' site conditions.

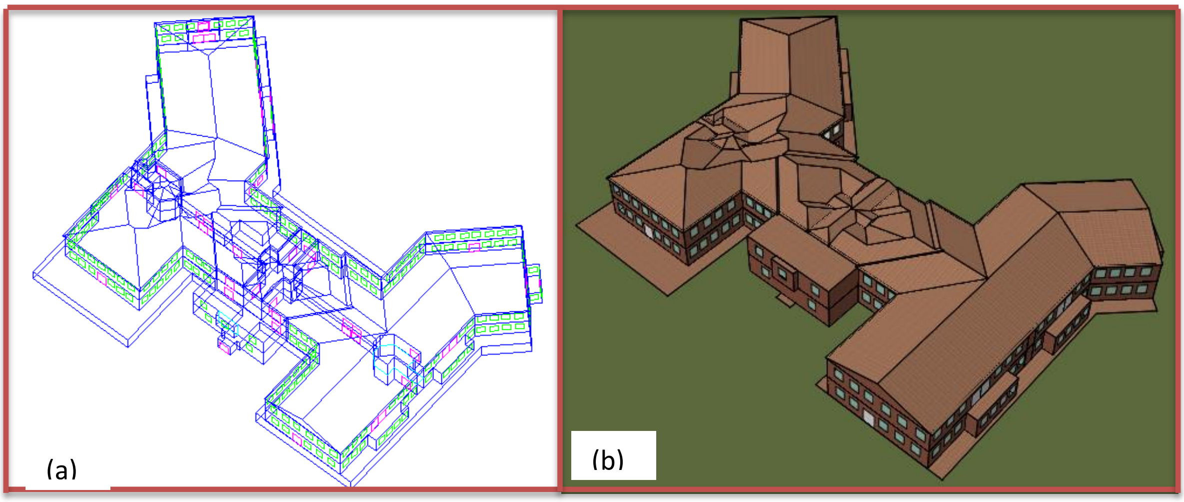

Figure 27: Frosterley Crescent building complete model in frame (a) and rendered (b) views.

The structure of the building was initially analysed with heavyweight concrete components at a density of 2400kg/m^3. A second model was subsequently created with heavyweight concrete replaced with lightweight concrete surface bed as well as reinforced concrete slabs. All other construction options including building elements, materials, and material properties remained consistent between the two models, such that the type of concrete used was the variable under investigation. After simulating both models based on the heat balance method, the program calculated the sensible cooling and heating loads summarised in the next section.

5.6.1Results:

Heating Plant Sensible Loads (Model 2A/B)

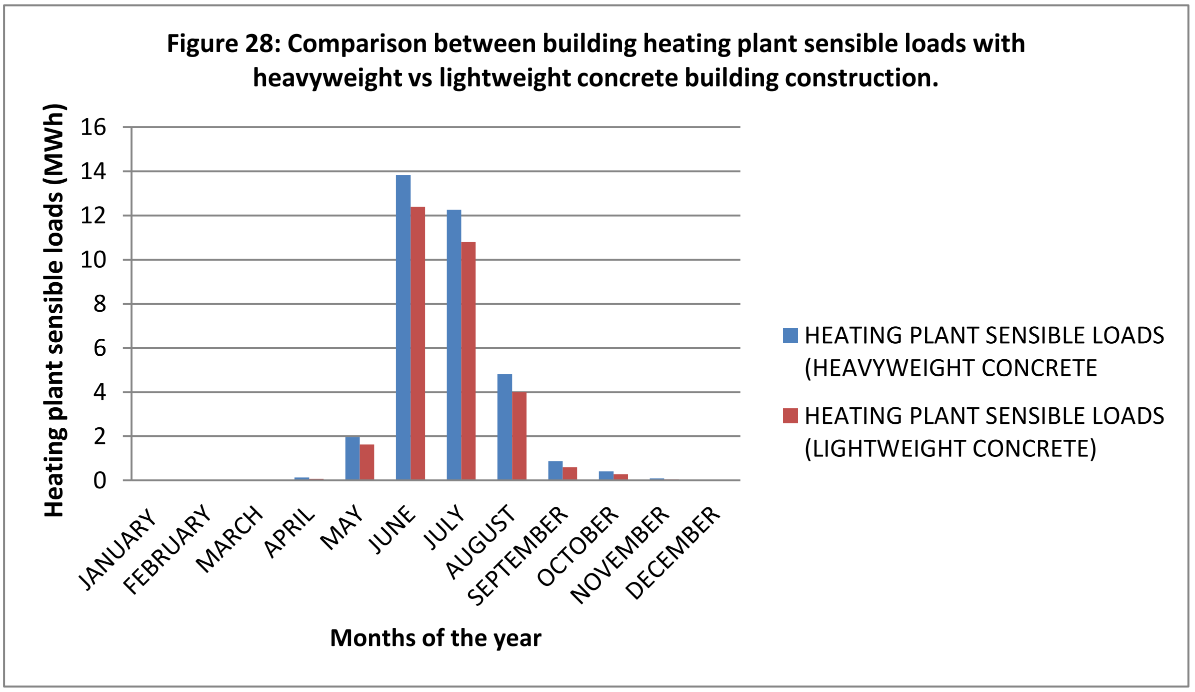

Figure 28: Comparison between building heating plant sensible loads with heavyweight vs lightweight concrete building construction.

Figure 28 indicates the heat required for keeping internal office temperature to a consistent temperature at 22°C. The heat required was measured in MWh for each month. In comparison to the Johannesburg office building, it is evident that the heating energy loads are significantly less. This can be attributed to the warm and humid climate experienced in Durban as analysed in the psychrometric charts (see Appendix C). Heating during office hours (6:30am-6:30pm) is not required from November to April. Most of the heat required is during mid-winter months of June and July. Interestingly, the building model analysed with lightweight concrete seems to be the favourable concrete construction type for heating loads within the office space as less heating load is required.

Table 12 highlights the saving in heating load (MWh) as well as a percentage difference between lightweight and heavyweight concrete performance throughout the year.

Table 12: Total annual heating energy loads and potential energy savings acquired from the difference between lightweight and heavyweight concrete construction.

	Model 2A (Baseline)	Model 2B		
	Heavyweight concrete construction (MWh)	**Lightweight concrete construction (MWh)**	**Total monthly savings MWh)**	
January	0,0015	0	0,0015	
February	0,0011	0	0,0011	
March	0,0007	0	0,0007	
April	0,13	0,08	0,06	
May	1,97	1,63	0,34	
June	13,83	12,40	1,43	
July	12,27	10,79	1,47	
August	4,82	4,00	0,82	
September	0,87	0,60	0,27	
October	0,41	0,29	0,13	
November	0,10	0,05	0,05	
December	0,003	0	0,003	
Total annual heating loads required (MWh)	34,40	29,82	**4,58**	**Total annual energy load difference (MWh)**

The total heating load over a year for heavyweight concrete construction amounted to 34.4MWh. This figure is approximately 72% less than the heating required for the Johannesburg case study office building under heavyweight construction. Lightweight concrete construction for this case study was more favourable than the heavyweight concrete construction option and equated to 29.82MWh. A total energy savings of 4.58MWh was attained from the utilisation of lightweight concrete over heavyweight concrete. This amounted to 13% savings in energy loads required for heating. However, due to the annual hot and humid climate in Durban, the energy required for cooling was more significant.

Cooling Plant Sensible Loads (Model 2A/B)

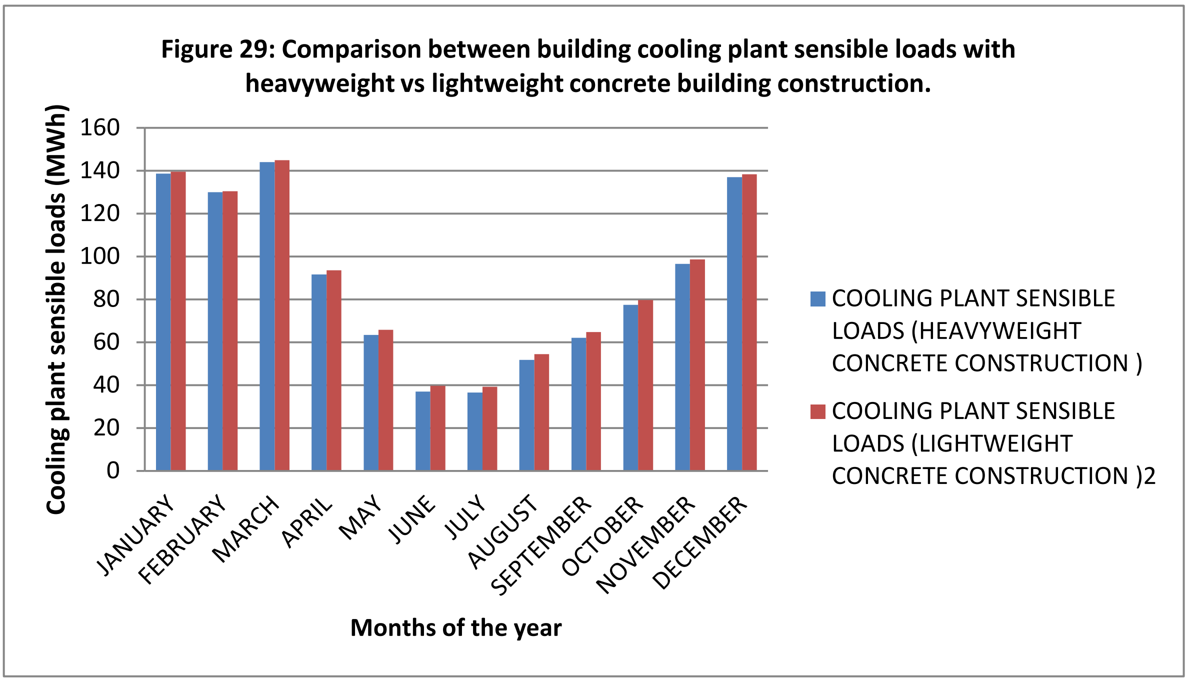

Figure 29: Comparison between building cooling plant sensible loads with heavyweight vs lightweight concrete building construction.

Figure 29 indicates the energy required per month to remove excessive heat from the internal office environment in order to attain a consistent comfortable temperature of 22°C (which is optimal for productivity in an office environment). From the results obtained, a significant portion of energy is required to cool the office building throughout the year. During the months December to January, energy required for cooling amounts to approximately 140MWh per month. Conversely to the heating load results, heavyweight concrete construction is shown to be more favourable compared to lightweight concrete construction in terms of energy savings required for cooling. Lightweight concrete construction consistently requires more energy to cool a space throughout the year for this specific site. The difference in MWh between heavyweight and lightweight concrete construction is highlighted in the Table 13.

Table 13: Total annual cooling energy loads and potential energy savings acquired from the difference between lightweight and heavyweight concrete construction.

	Model 2A (Baseline)	Model 2B		
	Heavyweight concrete construction (MWh)	**Lightweight concrete construction (MWh)**	**Total energy difference MWh)**	
January	138,74	139,53	-0,79	
February	130,01	130,52	-0,50	
March	144,08	144,94	-0,86	
April	91,71	93,53	-1,82	
May	63,40	65,76	-2,35	
June	36,94	39,70	-2,77	
July	36,59	39,23	-2,64	
August	51,82	54,43	-2,61	
September	62,06	64,77	-2,71	
October	77,39	79,62	-2,23	
November	96,52	98,71	-2,19	
December	136,98	138,34	-1,36	
Total annual cooling load required (MWh)	1066,23	1089,08	-22,85	**Total annual energy load difference (MWh**

The total heating load utilised over a year for heavyweight concrete construction amounted to 1066.23MWh versus the total heating load for lightweight concrete construction which equated to 1089.08MWh. This is significantly greater than the heating loads with heavyweight concrete which relates directly to the climate and occupancy hours of the office building (6:30am to 6:30pm).

Considering heavyweight concrete as the existing construction type, it is evident that this is the favourable construction type as less cooling load is required to obtain a constant internal temperature. Lightweight concrete construction, for this particular case study, would require an extra annual energy load of 22.85MWh compared to heavyweight concrete construction.

Accumulated heating and cooling energy loads.

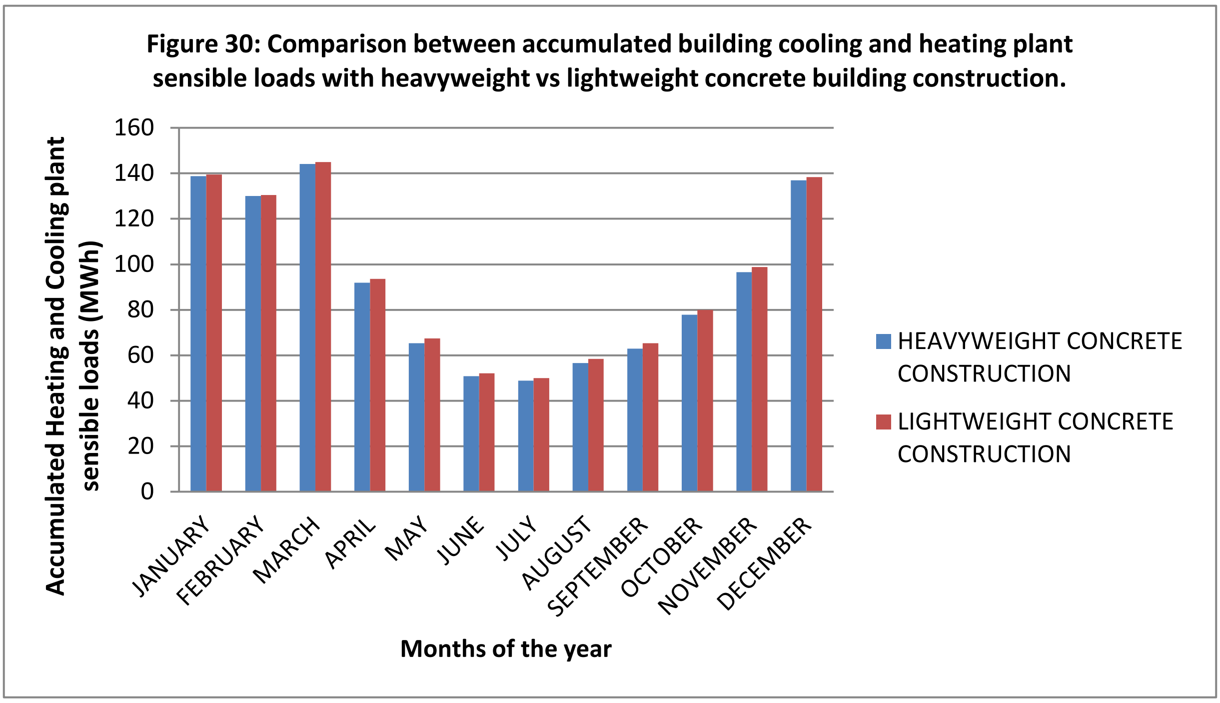

Figure 30: Comparison between building plant sensible loads with heavyweight vs lightweight concrete building construction.

Figure 30 shows the accumulated heating and cooling energy loads required for keeping an internal temperature at 22°C. The results indicate that heavyweight concrete is a more favourable form of construction material compared to lightweight in terms of efficiently utilising thermal mass to aid in internal temperature regulation in the office building.

Table 14 evaluates for the most favourable cooling and heating loads between both heavyweight and lightweight concrete construction for the year and determines what percentage of this load is attributed to heavyweight and lightweight concrete.

Table 14: Total annual energy loads showing the least energy required for heating and cooling between heavyweight and lightweight concrete construction.

	Least energy required per month for heating and cooling loads (MWh)	**Favourable concrete type (Heavyweight /Lightweight)**	**Percentage of energy load required per month (%)**	**Percentage of energy load required per month due to heavyweight concrete construction (%)**	**Percentage of energy load required per month due to lightweight concrete construction (%)**
JANUARY	138,74	Heavyweight	12,61	12,61	-
FEBRUARY	130,01	Heavyweight	11,81	11,81	-
MARCH	144,08	Heavyweight	13,09	13,09	-
APRIL	91,84	Heavyweight	8,34	8,34	-
MAY	65,37	Heavyweight	5,94	5,94	-
JUNE	50,77	Heavyweight	4,61	4,61	-
JULY	48,86	Heavyweight	4,44	4,44	-
AUGUST	56,64	Heavyweight	5,15	5,15	-
SEPTEMBER	62,93	Heavyweight	5,72	5,72	-
OCTOBER	77,80	Heavyweight	7,07	7,07	-
NOVEMBER	96,62	Heavyweight	8,78	8,78	-
DECEMBER	136,98	Heavyweight	12,45	12,45	-
TOTAL	**1100,64**		100,00	**100**	**0**

It is evident from the table above that 100% of construction under heavyweight concrete construction is attributed to less energy utilised for combined heating and cooling energy loads. Whereas lightweight concrete construction is unfavourable and results in higher energy loads utilised for heating and cooling throughout the year.

5.7 Feasibility study

Table 15: Energy cost savings / losses due on the implementation of lightweight concrete versus heavyweight concrete

Frosterley Crescent - Durban			
Passive energy intervention due to thermal mass			
	Total accumulated energy loads required (kWh)	**Cost / kWh**	**Derived total cost (R)**
Total energy required with heavyweight concrete construction. (Baseline scenario)	1100630,00	1,26	R 1 386 793,80
Total energy required with lightweight concrete intervention.	1118900,00	1,26	R 1 409 814,00
Difference in total energy required per year (saving/loss	-18270,00		**-R 23 020,20**
			Loss
Estimated cost of concrete / m3	**Total Volume (m3)**	**Cost / m3**	**Total cost**
Surface bed + internal concrete slabs (Heavyweight)	1151,23	R 1 242,22	R 1 430 080,93
Surface bed + internal concrete slabs (Lightweight)	1151,23	R 3 872,22	R 4 457 815,83
Difference in construction costs between lightweight and heavyweight concrete for this case study			**R 3 027 734,90**
Payback period - return on investment	**Total cost**		
Total cost of lightweight concrete intervention	R 4 457 815,83		
Energy cost savings/loss per working day	**-R 88,54**	Loss	
Pay back period	No pay back period as a loss of R88,54 is being accumulated each working day.		
Limited period of return on investment:	N/A as cost of lightweight concrete construction is greater than baseline heavyweight concrete construction.		

Table 15 shows the feasibility of implementing lightweight concrete compared to heavyweight concrete and the potential energy cost savings that can be acquired through the implementation of these thermal mass construction types. Firstly, the total annual loss per year when lightweight concrete is utilised amounts to R23 020. Secondly, the cost of lightweight concrete per cubic metre is approximately 3 times the cost of standard 25MPa heavyweight (2400kg/m^3) concrete. Therefore, it is neither favourable nor feasible to use lightweight concrete for this site and similar type of buildings situated in Durban.

Chapter 6: Conclusion and recommendations.

6.1 Findings and overall conclusions

This study has analysed the effects of heavyweight and lightweight concrete as thermal mass material on the overall building energy loads for heating and cooling in office buildings situated in the climate regions of Johannesburg and Durban. The objective of the study was to provide insight on thermal mass selection and its potential for energy savings towards reducing reliance on HVAC systems for indoor thermal comfort. This Chapter substantiates each sub-question as formulated in Chapter 1 as a means to comprehensively address the main research question: How can the dual role of concrete elements as structural systems and thermal mass be adapted and optimised towards energy efficiency through passive cooling and heating for office buildings under different climatic regions of South Africa?

6.1.1 Sub- Question 1

How do daily and seasonal temperature cycles influence thermal comfort within buildings and which passive energy interventions can be utilised for optimising thermal comfort, under different climatic zones of South Africa?

In order to achieve indoor thermal comfort, one of the main factors to take into consideration is the daily and seasonal temperature cycles. Firstly, it is important to understand that each geographic region experiences unique climatic conditions. Based on the insights from psychrometric charts both Johannesburg and Durban climate regions were assessed by analysing the influence of daily and seasonal temperature cycles on thermal comfort.

Based on the assessment, Johannesburg experiences a moderate climate, with varying, but sub-optimal humidity conditions with warm summers and cool winters. Mean minimum and maximum temperatures are 20°C and 30°C in summer and 9°C and 21°C in winter. This shows relative consistency between the differences in daily minimum and maximum temperatures (around 10°C) which has been proven to favour heavier thermal mass applications in terms of achieving thermal comfort through passive interventions. Furthermore, various passive interventions can be implemented to the building to reduce the overall energy loads used for heating and cooling. Some of these passive interventions include the addition of sun shading to the northern façades and including more landscaping and trees to the eastern façade and thermal mass alternatives for reducing building operational energy.

In contrast, the climate in Durban can be characterised as warm and humid, with minimum and maximum temperatures at 25°C and 32°C in summer and 16°C and 29°C in winter. High humidity in this climate region induces a feeling that it is warmer than it actually is thus requiring more energy for cooling internal building spaces. Therefore cost effective dehumidifying techniques (such as: natural ventilation if the outside moisture in the air is lower than the inside, running a fan to reduce moisture in air, placing containers of desiccant in the building and the introduction of more vegetation for evapotranspiration) should be considered. If buildings in Durban are designed with optimisation of passive control methods, this would reduce the need to rely so heavily on HVAC systems, predominately for cooling energy loads. With the additional heat due to internal heat gains, cooling loads are more substantial than heating loads for both climate regions.

6.1.2 Sub-Question 2

Given structural performance priorities, what would be the responsive thermal mass variations for concrete in line with thermal comfort needs and temperature cycles for various climatic zones of South Africa?

The adaptation of structural thermal mass to influence building thermal performance can be valuable in terms of energy savings. Literature appraisal in Chapter 2 indicated that heavyweight concrete thermal mass (at around 2400kg/m^3) has excellent structural properties with a high compressive strength, and stiffness (elastic modulus). In contrast, lightweight concrete (at around 1200kg/m^3), is characterised by lower elastic modulus compared to heavyweight concrete which results in structures being more prone to deflections. However, this can be overcome by appropriate structural design and reinforcement detailing.

Based on the simulated results of the two storey office buildings (for Johannesburg and Durban), heavyweight high density concrete is favourable for reducing overall cooling energy loads in both moderate and humid climate regions where there is a difference in minimum and maximum temperature of approximately 10°C. This falls in line with the theory of favourable thermal mass performances in regions that experience a significant difference in day and night temperatures.

In contrast, lightweight concrete is favourable in reducing overall heating energy loads during peak winter months only. This may be attributed to the lower thermal conductivity that lightweight concrete possesses over heavyweight concrete. In line with literature reviewed and the results obtained in Chapter 5, favourable insulation properties (low thermal conductivity) inherent in lightweight concrete has proven to reduce heating energy loads in both Johannesburg and Durban climatic regions.

6.1.3 Sub-Question 3

What would be the optimised heating and cooling energy load outcomes of the thermal mass variation (lightweight concrete versus normal/heavyweight concrete) for the different climatic zones of South Africa?

The simulated results indicate that from an overall heating and cooling load, baseline heavyweight concrete construction is the favourable option for both case study buildings (Johannesburg and Durban). The results showed that required heating energy loads is less for lightweight concrete construction than heavyweight concrete construction. However, cooling energy loads exceed the heating loads as they account for 85% and 96% of total energy loads required for heating in and cooling in Johannesburg and Durban respectively. The high cooling loads may be attributed to a significant amount of internal gains from office, lighting, equipment and occupancy. Whereas, the results obtained for Johannesburg follows theoretical expectations given the climatic conditions. The findings for Durban contradicts initial expectations that lightweight concrete would be more favourable in view of Durban's hot and humid climate. This possibly implies that Durban's climate may not be consistently hot enough for lightweight concrete to be favourable. Even though humidity levels are consistently high, there is still a significant difference between daily minimum and maximum temperatures which would thus warrant the thermal properties of heavyweight concrete.

6.1.4 Sub-Question 4

What would be the economic viability of thermal mass variations in comparison to the energy savings arising from the energy efficiency gains across the various climate zones?

Given that lightweight concrete is a specialised concrete that requires concrete distributors to create a specific mix batch according to engineers specifications, the cost per cubic meter is relatively higher than standard concrete mixes. As highlighted in Chapter 5, the cost of lightweight concrete at 25MPa and 1200kg/m^3 per cubic meter in relation to standard heavyweight concrete 25MPa and 2400kg/m^3 per cubic meter is approximately 3 times more.

Results obtained from the study show that heavyweight concrete is favourable in both climatic regions of Johannesburg and Durban. The total accumulated energy load with baseline heavyweight concrete construction in Johannesburg (as simulated with IES_VE model) were calculated as 620.00MWh, whereas lightweight concrete had an accumulated heating and cooling energy load of 629.00MWh. Therefore, not only is more energy required for the lightweight concrete option, but its overall cost is higher as well. This results in an overall loss being accumulated daily over the life of the building. Similarly for the case study building in Durban, accumulated energy load for heavyweight concrete was calculated as 1100.63MWh, whereas the outcome for lightweight concrete construction was 1118.90MWh. Once again, more energy is required for lightweight concrete construction and the overall initial construction cost is more expensive than utilising standard heavyweight concrete.

6.2 Overall consolidation towards the findings in response to the main research question.

From the analysis carried out in this study, it can be concluded that two storey office buildings constructed from heavyweight thermal mass concrete, performs better than lightweight concrete in both moderate climate regions with sub-optimal humidity (similar to Johannesburg) and in hot and high humid sub-tropical climate regions (similar to Durban). Heavyweight concrete was expected to be favourable in moderate climates with a high diurnal range and lightweight concrete in hot and humid sub-tropical climates with a low diurnal range. Results showed that a diurnal range of approximately 10°C is significant to favour heavyweight concrete even in climate regions with high humidity. Thus expectation for lightweight concrete to perform better than heavyweight concrete in Durban were contrary to expectations. However, lightweight concrete showed enhanced insulation properties compared to heavyweight concrete, which favoured heating energy loads under both climatic regions.

This study appraised two office buildings in different climatic regions. General inferences on thermal mass performance on these climate regions should be undertaken cautiously as many varying factors play a role in determining the heating and cooling energy loads in buildings which includes thermal mass adaptations. Current standards such as SANS 204:2011 offers little explanation, but no guidance on the design and implementation of thermal mass for energy efficiency in buildings. Revised versions of this code could address this by suggesting strategic material response for thermal mass under various climatic regions.

Since thermal mass has the ability to influence indoor temperature, and thus reduce energy consumption in buildings through improving human comfort, it is considered a crucial component towards the passive design of energy efficient buildings. This has implications for energy efficiency regulations under the diverse climatic regions.

6.3 Further Research Recommendations

Insights from this study have highlighted various avenues to pursue further investigation into the influence of thermal mass on building energy efficiency. Based on the study, this section highlights recommendations for further research.

6.3.1 Climate regions under consideration.

As highlighted in the conclusion, the use of heavyweight concrete is favourable in moderate climate regions such as Johannesburg where there is a significant difference in maximum and minimum temperatures. Even Durban's climate (which is normally regarded as warm and humid) showed a daily difference in temperature that was significant enough to warrant heavyweight concrete. Based on the findings of the study as well as theoretical knowledge of thermal mass applications, lightweight concrete applications should be investigated in climate regions that exhibit minimal variation in daily temperature regimes. Inter-tropical areas that are closer to the equator may be more favourable to the advantages of lightweight concrete construction compared to the two sub-tropical climate conditions covered in this study.

6.3.2 Variations of thermal mass

Further studies may also focus on additional variations in heavyweight vs lightweight concrete, thus calling for investigations into a range of alternative densities that may be appropriate for specific climatic regions. With the application of more specialised concrete mixes being used in industry, studies into the optimised concrete strength-to-density ratio to reduce overall heating and cooling energy loads required in a building may be worthwhile to investigate further. Although the costs of specialised concrete mixes are relatively more expensive than standard heavyweight concrete mixes, finding climate regions where lightweight concrete is beneficial could result in an acceptable return on the initial investment. In addition, future studies can adopt life-cycle costing or present-value methods to calculate the return on investment.

6.3.3 Focus on building envelope and larger building applications and alternate sources of energy.

Focus could also specifically target buildings envelopes for the effects of lightweight vs heavyweight concrete applications or buildings with a larger overall concrete profile should F be studied. Analysis of external façade with direct interface between outside and inside thermal conditions might show more significant outcomes than assessing internal concrete slabs and beams only. In such cases, buildings with higher intensity of concrete use would be studied. Additionally, a comparison on the optimisation of other passive interventions may be worthwhile to pursue further as well as investigating alternate energy sources/ active energy interventions to understand to what extent building energy performance can be enhanced.

6.3.4 Overall analysis of concrete embodied energy versus thermal mass properties.

This research report focuses on the operating energy requirements for the building in terms of heating and cooling loads. The processing and manufacturing of building materials also have a significant off-site impact on total building energy consumed. Assessing whether thermal mass properties of various forms of heavyweight and lightweight concrete would offset their embodied energy is an interesting investigation to undertake. However the results would differ for varying climate regions.

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Appendix A

Key principles in passive thermal control

Key principles in passive thermal control

A.1 Regulating the internal building environment to achieve human comfort.

Assessing outdoor climatic conditions enables building designers to understand and design buildings that respond to climate variations in order to optimise on thermal comfort indoors with minimum energy consumption. In order to economically optimise a building space and create a comfortable internal environment, a building should be designed (through energy efficient means) to respond easily to climatic variations. Thermal comfort is influenced by air temperature, radiant temperature, humidity and air movement (Jones, 2016). The relationship between these variables and human comfort are highlighted in Table 16.

Table 16: Factors that affect thermal comfort within buildings. Source: Adapted from (Jones, 2016)

Factors influencing thermal comfort	**Human comfort**
Air temperature	This is the average air temperature in an occupied space. Human comfort temperatures range between 18°C and 26°C. Specifically for office areas, a regulated temperature of 21°C-22°C is usually preferred to stimulate a highly productive and comfortable environment.
Radiant temperature	Defined as a measure of the average temperature of the surrounding surfaces, radiant temperature can directly affect human comfort. Large variances in surrounding surfaces (eg: large windows) can lead to discomfort due to the variance of radiant temperature
Humidity	Human comfort is disturbed when high levels of humidity are experienced. To achieve comfortable and productive working environment, passive energy efficient interventions to dehumidify a space should be implemented to aid in retaining humidity levels between 40% and 60%.
Air movement	The movement of air influences the amount of heat loss from a body. In buildings, moving air through windows or fans can be used as a form of cooling for direct air flow. Higher temperatures are less uncomfortable in the presence of moving air.

As highlighted above, a key function of all buildings is to regulate the internal environment to achieve human comfort. Specifically within office buildings, a comfortable environment enables a better work space to think and be productive. In addition comfort contributes to health and wellbeing. Having stated this there are three main approaches to environmental control within buildings, these include active, mixed mode and passive environmental control methods. Firstly, active environmental control represents a highly controlled thermal environment through the use of energy intensive HVAC systems. Secondly mixed mode environmental control seeks a balance by utilising both HVAC systems (active) and passive means to create a comfortable internal environment. Lastly, passive environmental control uses passive design strategies and natural sources such as solar gains for heating, and crosswind ventilation for cooling to create a comfortable internal environment. Through good design, construction and maintenance thermal comfort can be achieved. (City of Johannesburg, Gauge, CSIR, 2008).

A.2 Macro-climates and micro climates

Macro-climate and micro-climate of the geographical location has a direct influence on the internal and external thermal environment. Therefore, it is important to assess both macro-climate and micro- climate conditions to understand the existing site conditions and to guide the designing of energy efficient buildings. The macro-climate refers to the climate of a larger area such as a region or a country, while the micro-climate refers to the variations in localised climate around the building. Main factors that affect the micro climate include the impact of trees and vegetation, types of surfaces, as well as topography. It is imperative to understand and get a holistic view of both the macro the micro climate for the sites under investigation as these will be the determining factors when carrying out a baseline energy performance analysis.

A.2.1 Macro-climate and the value of psychrometric charts

Assessing the differences in climatic conditions from one place to another or from season to season is crucial towards an understanding of the total energy consumed in buildings. Even though the climate in South Africa may not be as extreme as in other regions of the world, it is important that regional and seasonal variations be taken into account in the assessment and benchmarking of building energy performance.

Psychrometric charts are commonly used to analyse the climatic conditions in relation to a buildings internal requirements and thus guide the designer on identifying the passive heating and cooling interventions required to attain indoor thermal comfort, as well as whether additional active (mechanical) means of heating and cooling are required.

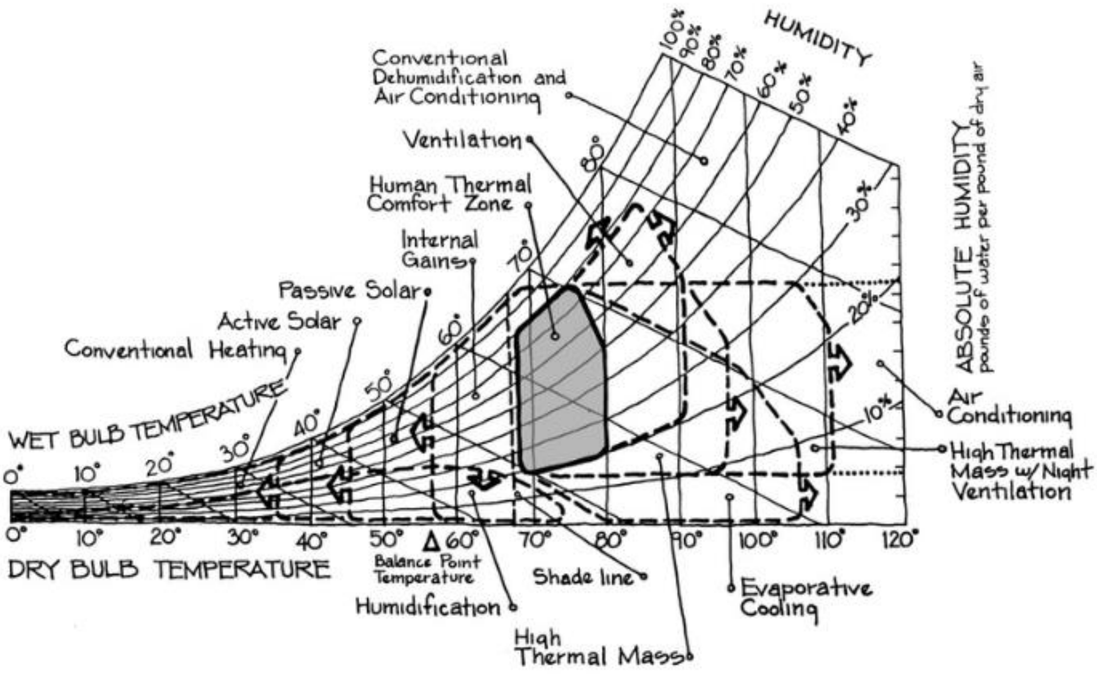
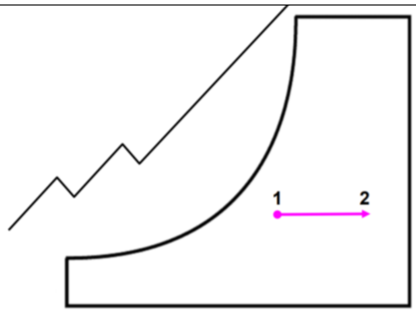
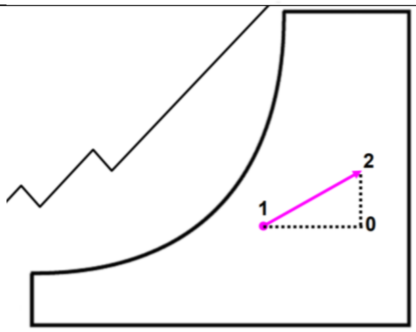
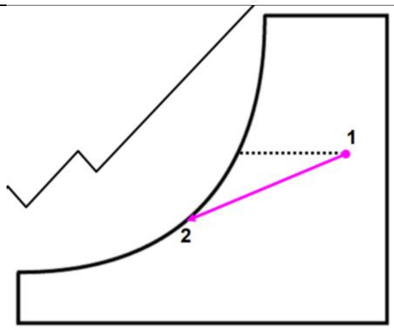
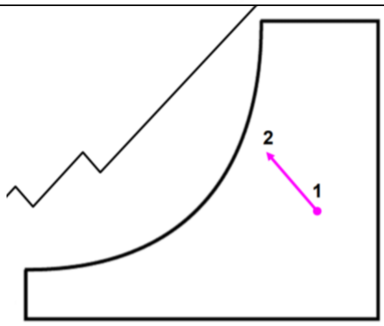
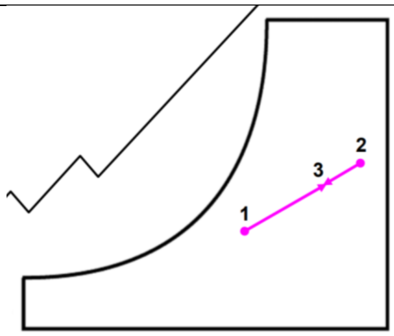


Figure 31: Typical psychometric chart. (Mansy, 2006)

Making use of a psychometric chart requires plotting multiple climate data points on the chart. These points represent the existing climate data and air conditions chosen at a specific time. The defined comfort zone is overlaid onto the chart. The comfort zone is defined as the range within which a majority of occupants are satisfied with the surrounding thermal conditions. By assessing the plot of data points the passive and active design strategies required to attain thermal comfort level become apparent. Figure 31 shows a typical psychrometric chart. A variance of dry bulb, wet bulb and relative humidity would thus influence the choice of passive interventions required to achieve indoor thermal comfort.

The various passive strategies proposed by a psychrometric chart is analysed in Table 17. When implemented, these strategies extend the thermal comfort zone towards the outdoor climate conditions.

Table 17: Strategies of passive design interventions in buildings that are proposed by the psychrometric chart. (Source: Adapted from Peralta, undated)

1.**Heating or cooling:** This psychrometric process involves the increase or decrease in the temperature of air without changing its humidity ratio.	
2.**Heating and humidifying** This psychrometric process involves the simultaneous increase in both the dry bulb temperature and humidity ratio of the air.	
3.Cooling and dehumidifying This psychrometric process involves the removal of water from the air as the air temperature falls below the dew-point temperature.	
4.**Adiabatic and evaporative cooling** This psychrometric process involves the cooling of air without heat loss or gain. Heat lost by the air is converted to latent heat in the added water vapour.	
5.**Adiabatic Mixing of moist air stream** This psychrometric process involves no net heat loss or gain during the mixing of two air streams	

A.2.2 Micro-climate

Impact of surfaces

Soil is considered as one of the most common surfaces. It regulates the micro climate through its retention and evaporation of water and affects the humidity and temperature of the air above. However, in city regions due to urban development, many surfaces have been paved to become 'hard surfaces' such as walkways, asphalt surfaced roads, concrete, and gravel. This has had a profound effect on micro climates as these hard surfaces interact very differently compared to the soil. Hard surfaces are more likely to absorb the heat than to reflect it. This results in solar energy heating the urban environment which is linked to surface reflectance of solar radiation. Less reflectance means that more energy is absorbed and stored, which subsequently warms the surrounding environment. This change in surface also contributes to the Urban Heat Island (UHI) effect, where buildings in cities require less heating during winter than suburban or rural areas. However, UHI effect also intensifies heatwaves thus affecting thermal comfort and reducing opportunities to passively cool buildings. (Oke, 1987) and (Gething and Puckett, 2013).

Impact of Trees and Vegetation

Trees and other vegetation assist in the regulation and control of ambient temperature. Specifically in an urban setting, trees help counteract the urban heat island (UHI) effect. Shading mitigates the urban heat island effect in two interconnected ways. Firstly, it achieves this is by restricting the amount of heat energy that the surfaces experiences, thereby reducing the level of heating available for the local environment to absorb. Secondly, it reduces the amount of direct gain of energy through windows, thus reducing the internal greenhouse effect, such that less energy will be required for air conditioning which in turn leads to energy and cost savings. The effectiveness of the shading that a tree can provide is determined by a variety of factors such as the tree species, canopy volume, crown shape and the tree's location and orientation in relation to a building Thus, the positioning of the tree in respect to the building can impact its ability to optimise energy conservation. (McPherson,1993).

Another means by which vegetation helps to offset the UHI effect is through evapotranspiration. This refers to the process whereby water within a plant, on its surfaces or in the soil is transformed into water vapour, utilizing the energy from the incoming solar radiation as the latent energy of evaporation. Other factors that can affect the effectiveness of evapotranspiration include the absence of leaves on deciduous trees and lower ambient temperatures are generally experienced during winter. The inclusion of vegetation can therefore create an oasis effect, where the maximisation of their evapotranspiration results in lower ambient temperatures and buildings consuming less cooling energy (McPherson,1993).

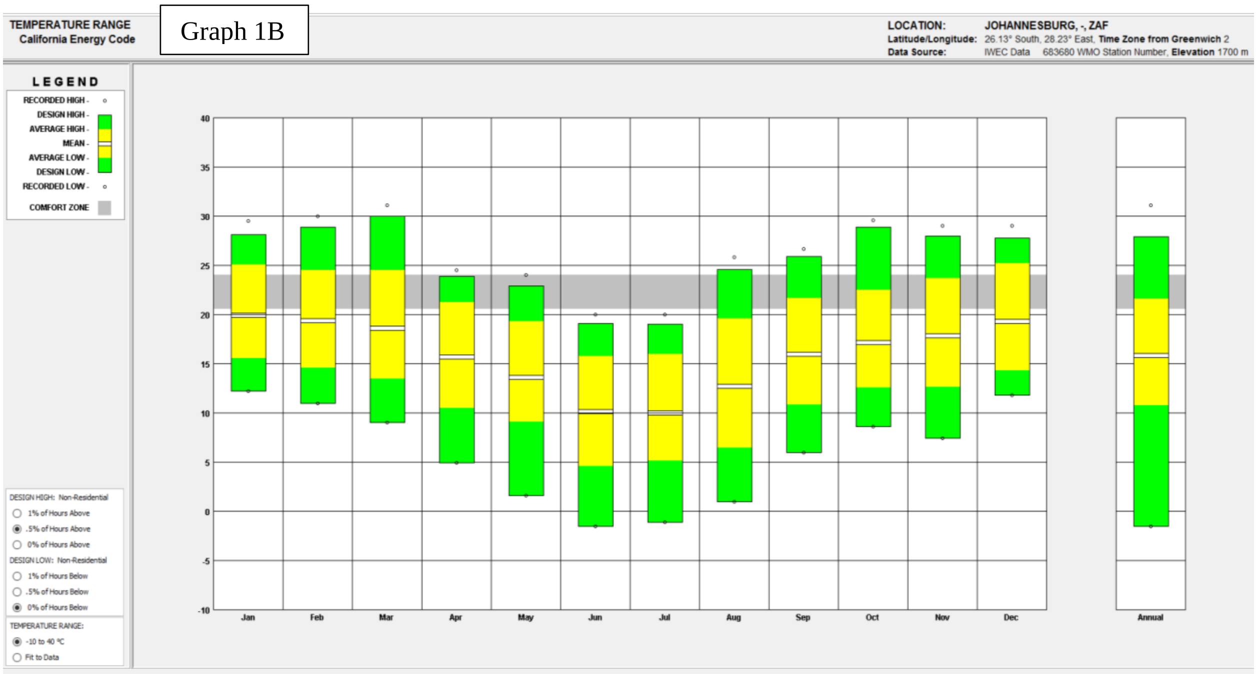
Impact of Topography

Topography relates to how the form of the land affects the site microclimate. Compared to macro-climates, micro-climates are more erratic due to the topographic features that characterise them such as their aspect and slope. Aspect is a term used to define the direction that the slope faces, especially because the direction determines how much solar radiation the site experiences, which in turn impacts on the temperature due to the shadow and shading. In South Africa, northern slopes receive the highest concentration of solar radiation. Another factor to take into consideration when studying topography is how it affects the wind and water on the site. Winds are often stronger at higher altitudes and the angle of slope on a geological feature is a major factor in determining the influence of wind and water on a site. The steeper the slope the faster the wind will flow uphill. In terms of water, a steeper slope means that water runs off the slope more quickly, meaning not only that it has less time to infiltrate into the soil, but is also more likely to cause erosion of the soil on the slope, particularly in areas of heavy rainfall. Furthermore, the altitude of the site will affect temperature, with locations higher above sea level being colder than those lower down. (Morakinyo *et al*, 2013).

Appendix B

Climate analysis – Johannesburg

(Adapted from Climate Consultant-EnergyPlus software program)


TEMPERATURE RANGE
California Energy Code
Graph 1B
LOCATION: JOHANNESBURG, -, ZAF
Latitude/Longitude: 26.13° South, 28.23° East, Time Zone from Greenwich 2
Data Source: IWEC Data 683680 WMO Station Number, Elevation 1700 m
LEGEND
RECORDED HIGH
DESIGN HIGH
AVERAGE HIGH
MEAN
AVERAGE LOW
DESIGN LOW
RECORDED LOW
COMFORT ZONE
Jan
Feb
Mar
Apr
May
Jun
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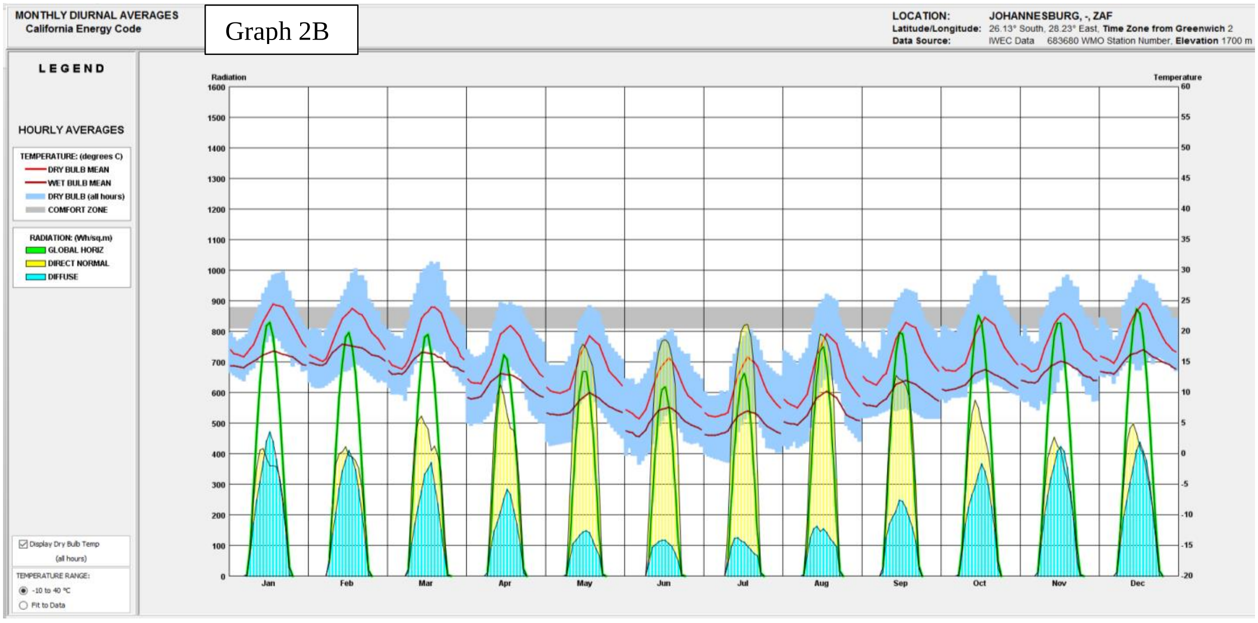
Sep
Oct
Nov
Dec
Annual


MONTHLY DIURNAL AVERAGES
California Energy Code
Graph 2B
LOCATION: JOHANNESBURG, -, ZAF
Latitude/Longitude: 26.13° South, 28.23° East, Time Zone from Greenwich 2
Data Source: IWEC Data 683680 WMO Station Number, Elevation 1700 m
LEGEND
HOURLY AVERAGES
TEMPERATURE: (degrees C)
DRY BULB MEAN
WET BULB MEAN
DRY BULB (all hours)
COMFORT ZONE
RADIATION: (Wh/sq.m)
GLOBAL HORIZ
DIRECT NORMAL
DIFFUSE
Radiation
Temperature
Jan
Feb
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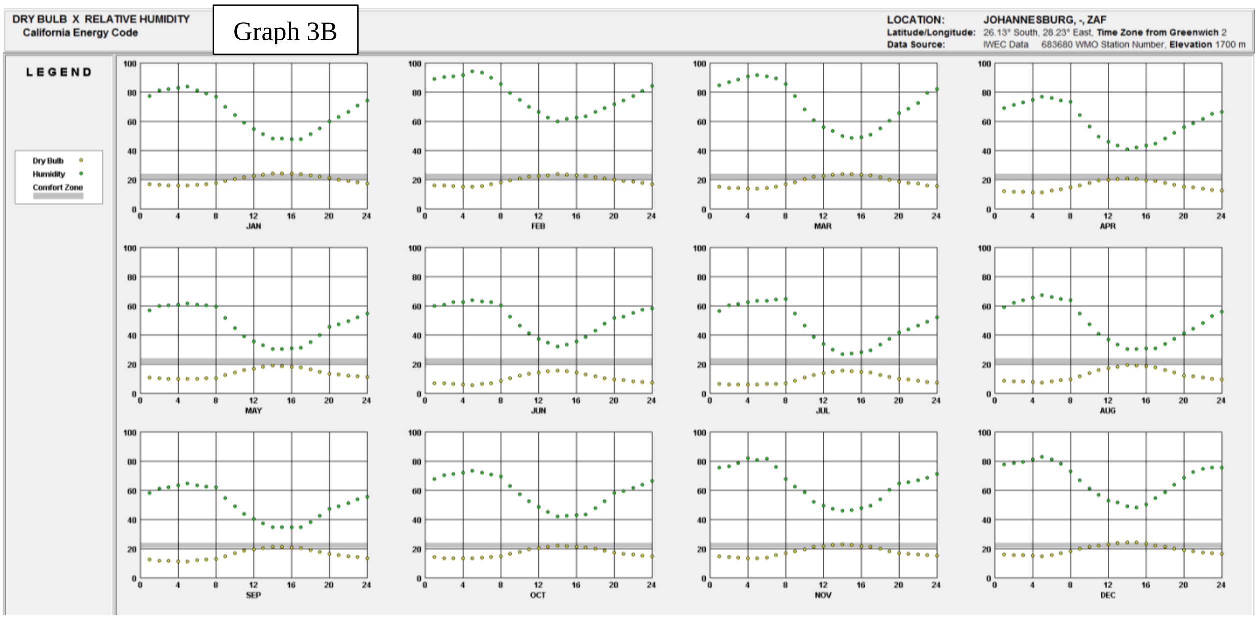
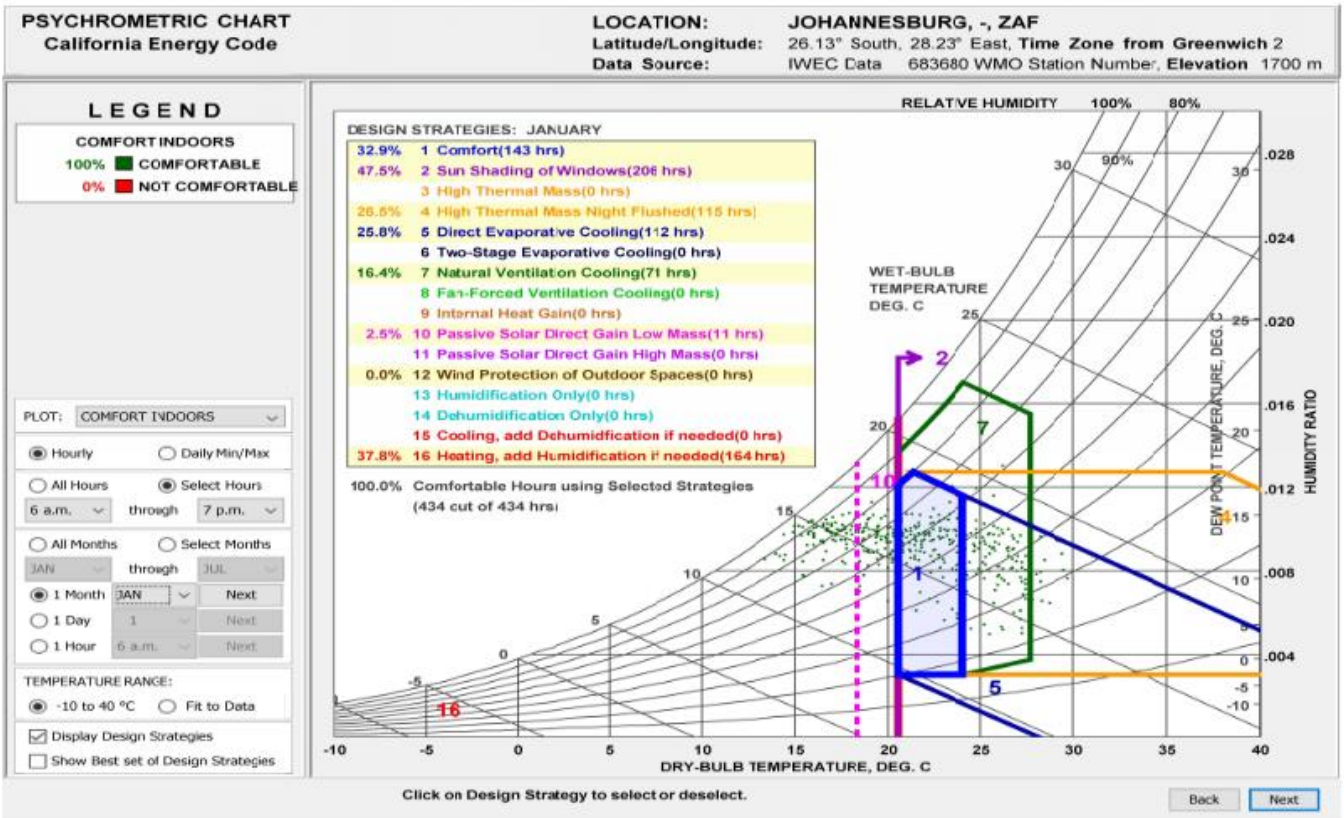
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

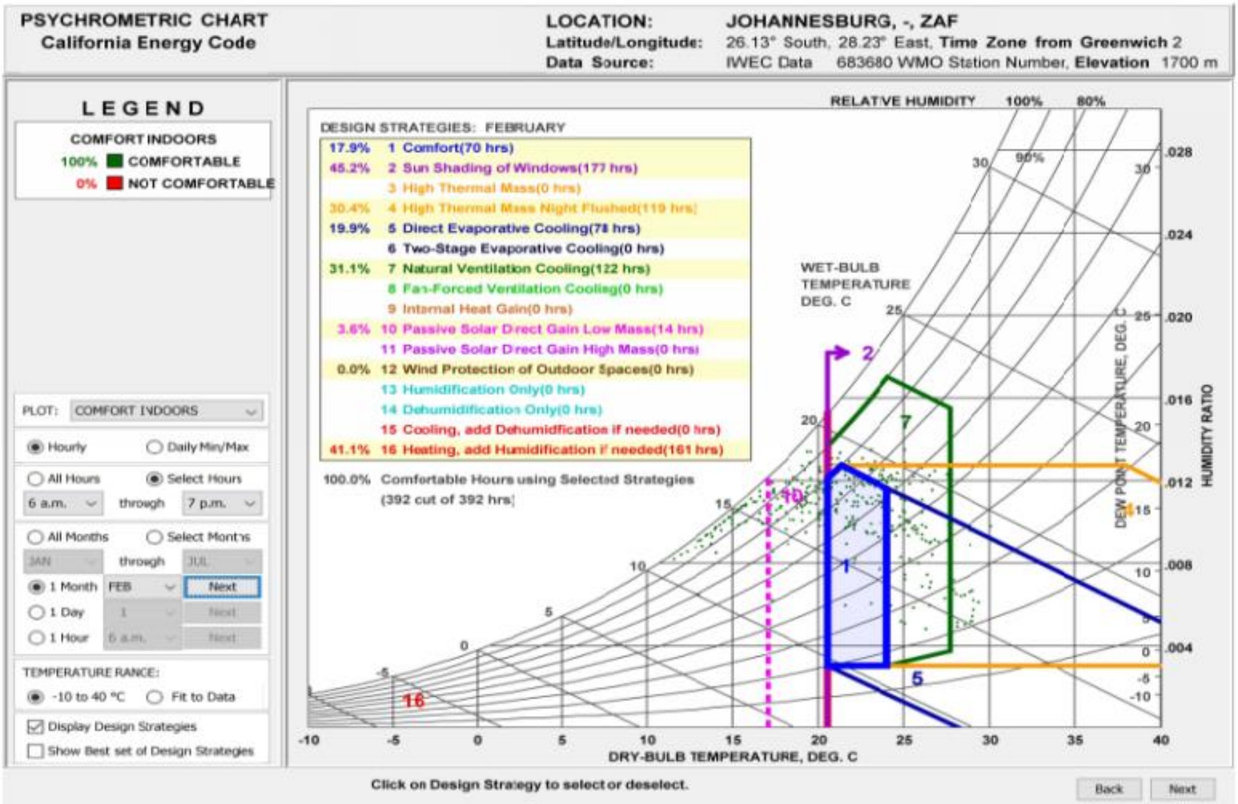

DRY BULB X RELATIVE HUMIDITY
California Energy Code
Graph 3B
LOCATION: JOHANNESBURG, -, ZAF
Latitude/Longitude: 26.13° South, 28.23° East, Time Zone from Greenwich 2
Data Source: IWEC Data 683680 WMO Station Number, Elevation 1700 m
LEGEND
Dry Bulb
Humidity
Comfort Zone
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC

JOHANNESBURG

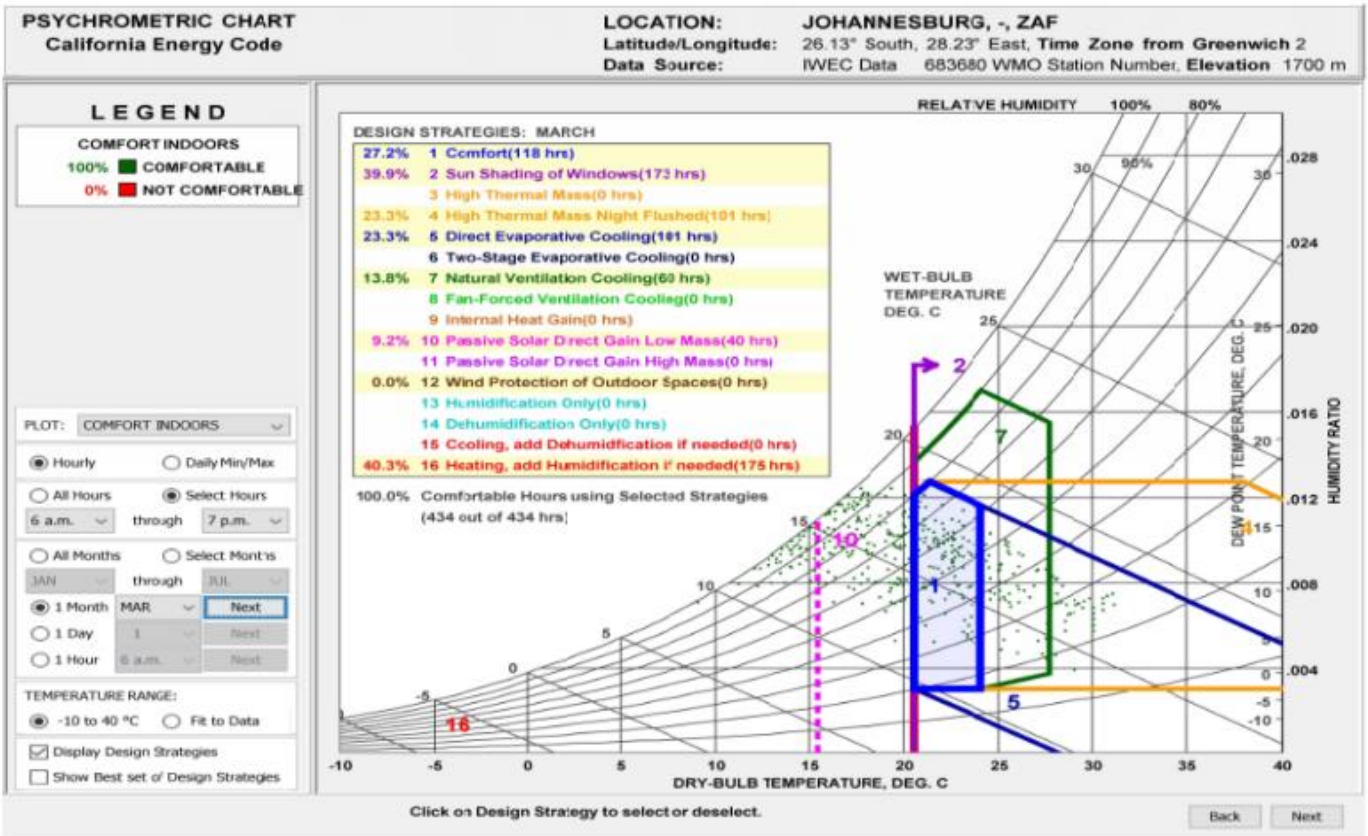
Psychrometric chart 1.1 – January



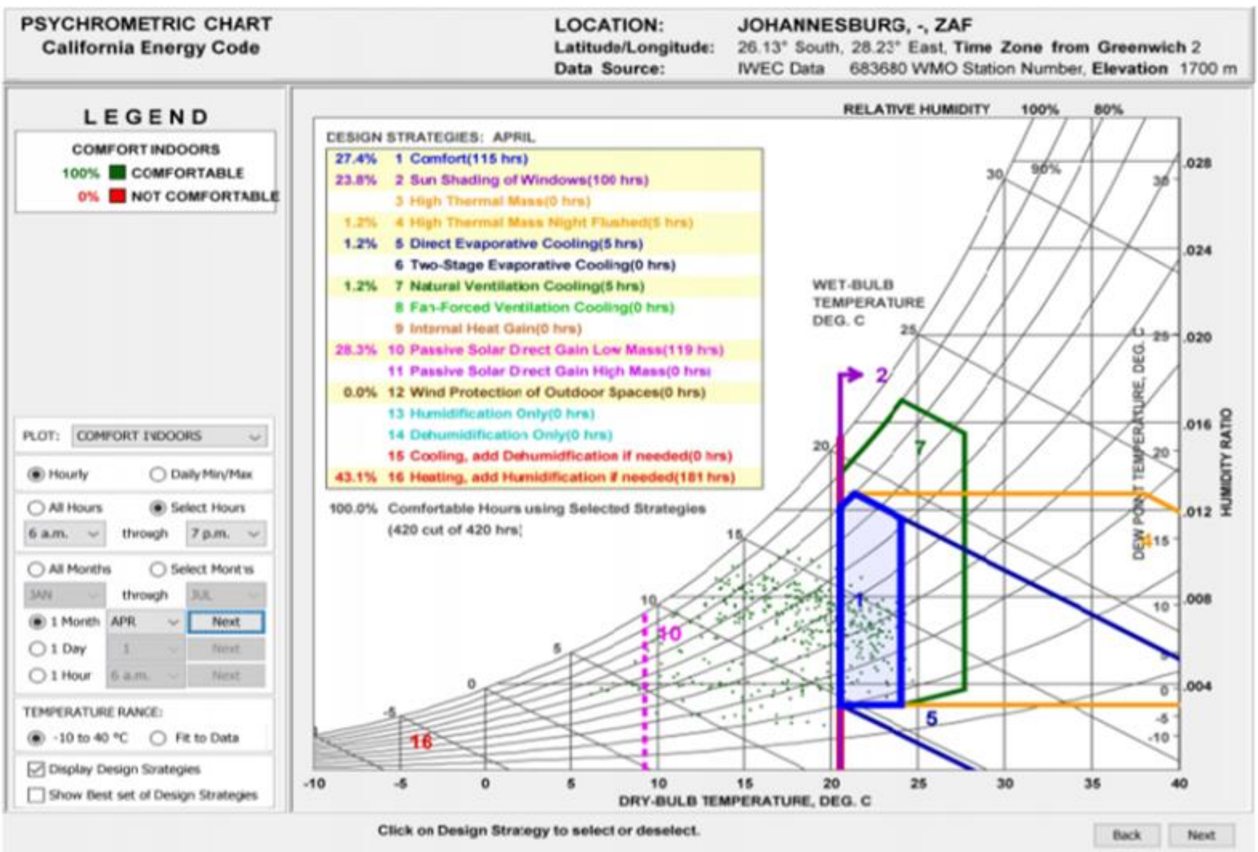
Psychrometric chart 1.2 – February



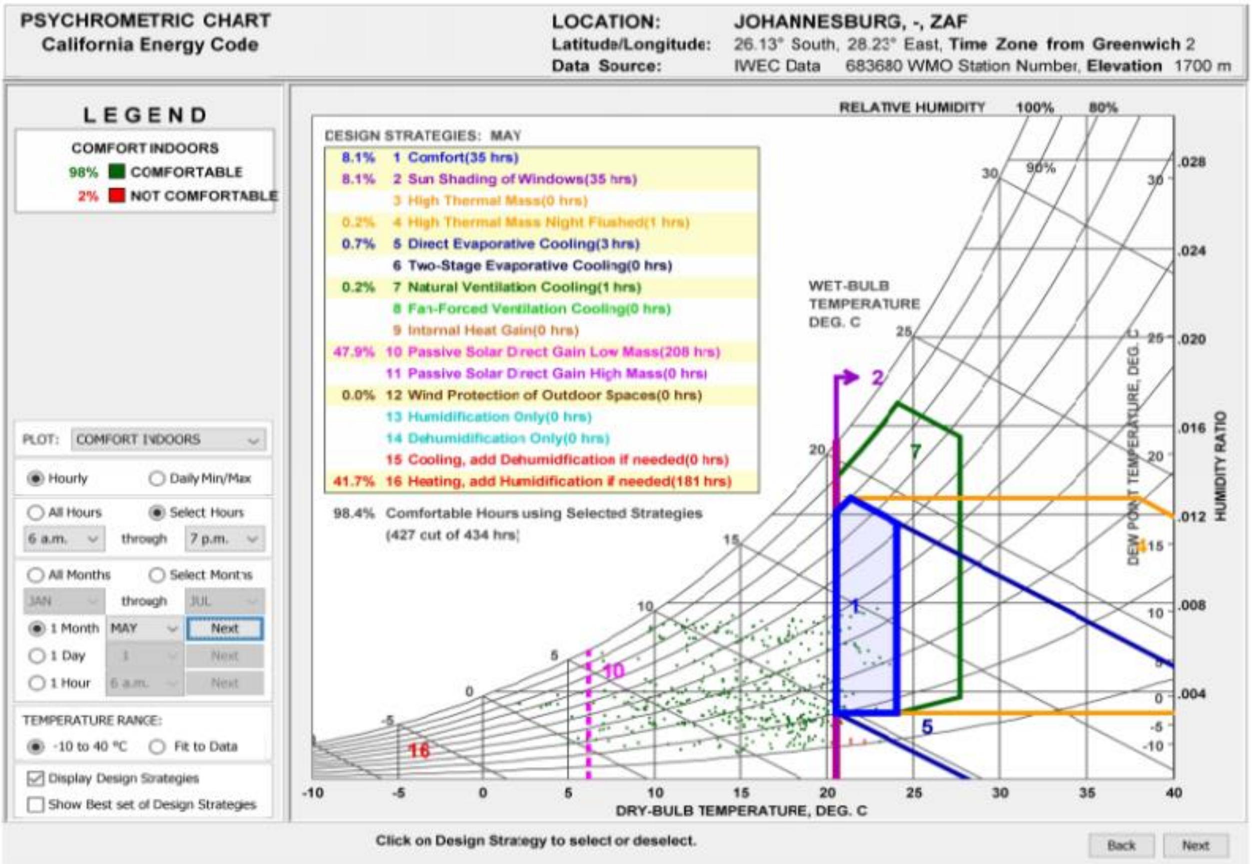
Psychrometric chart 1.3 – March



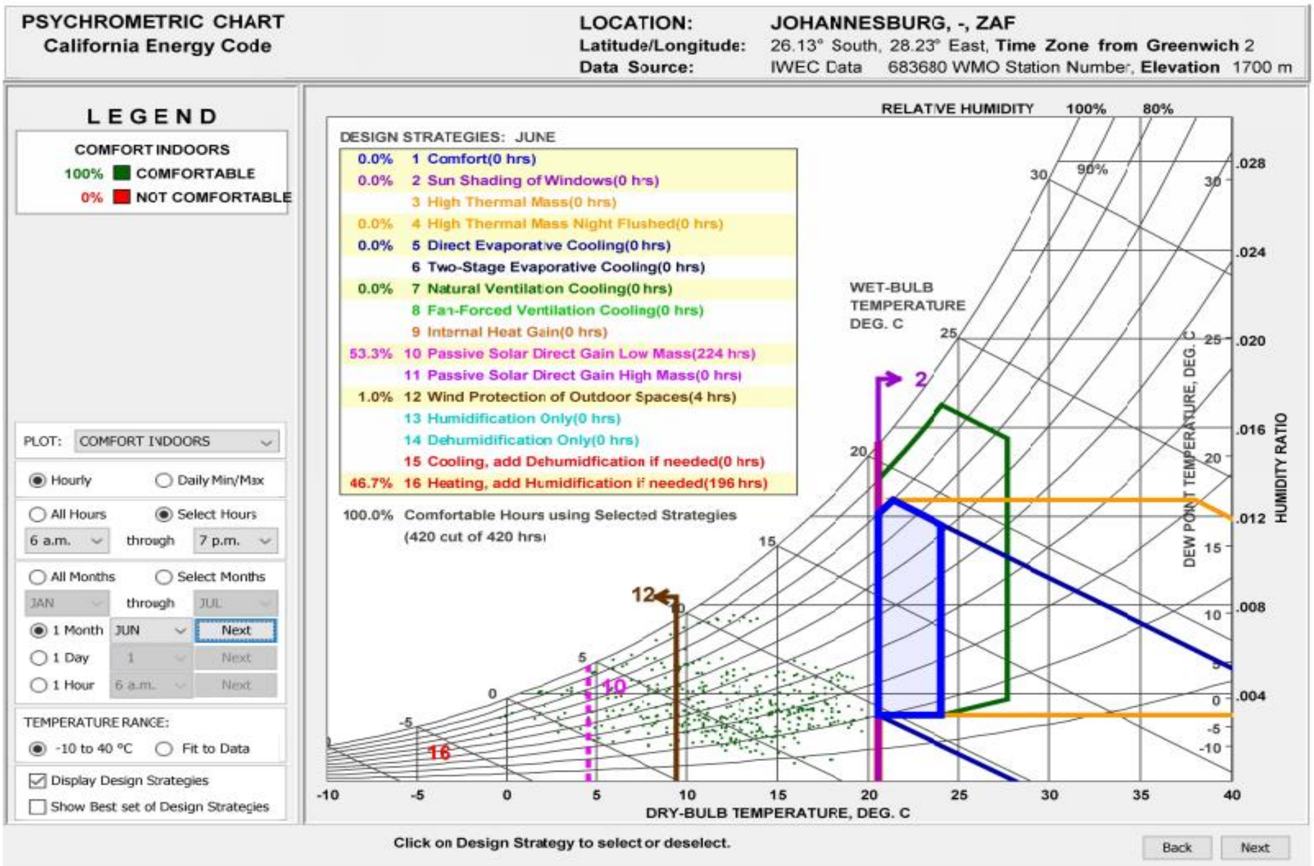
Psychrometric chart 1.4 – April



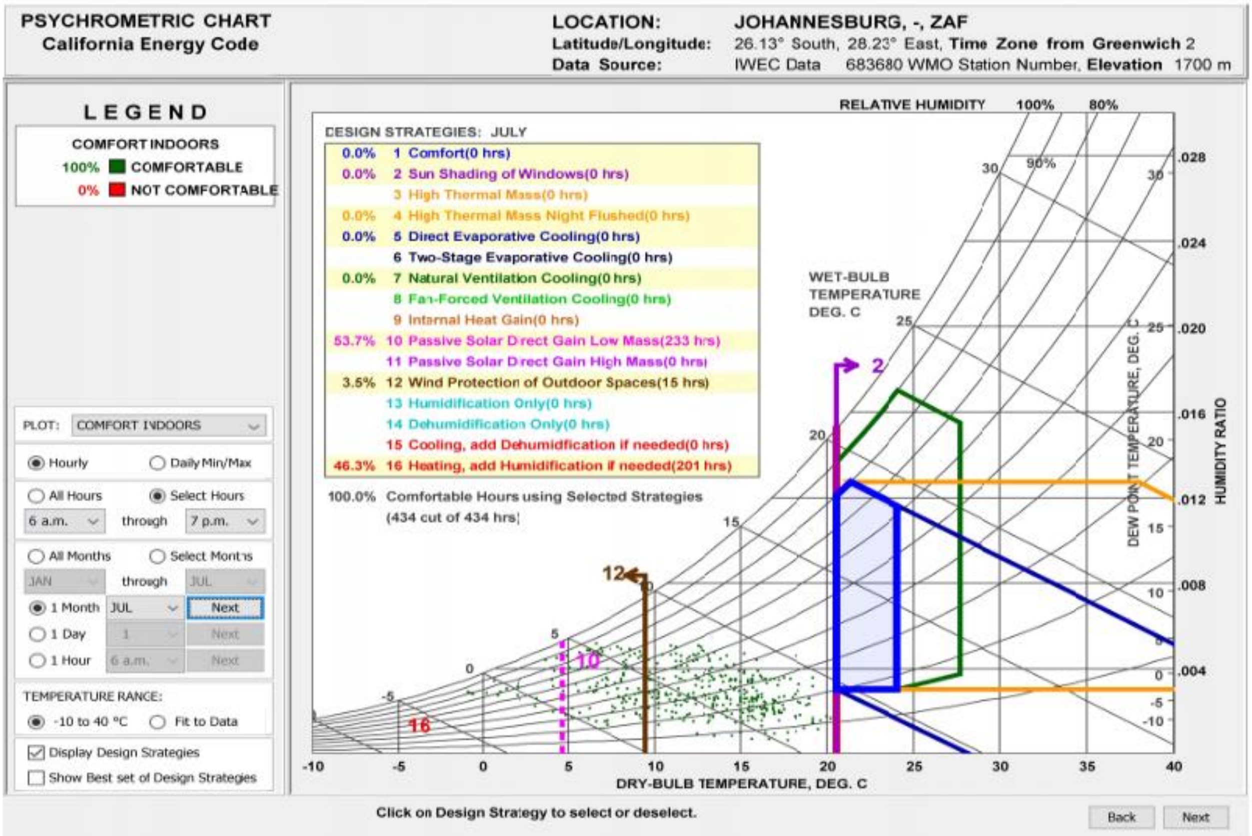
Psychrometric chart 1.5 – May



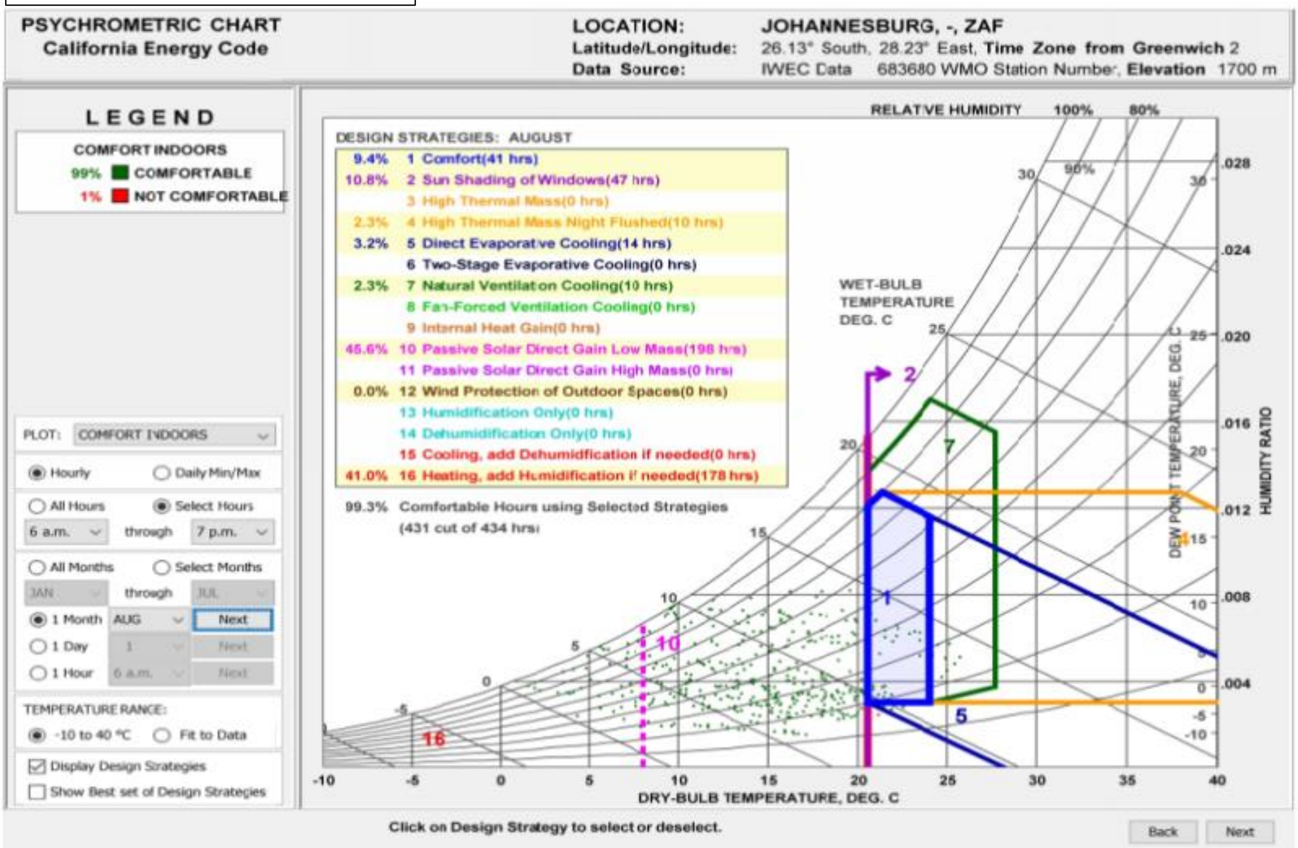
Psychrometric chart 1.6 – June



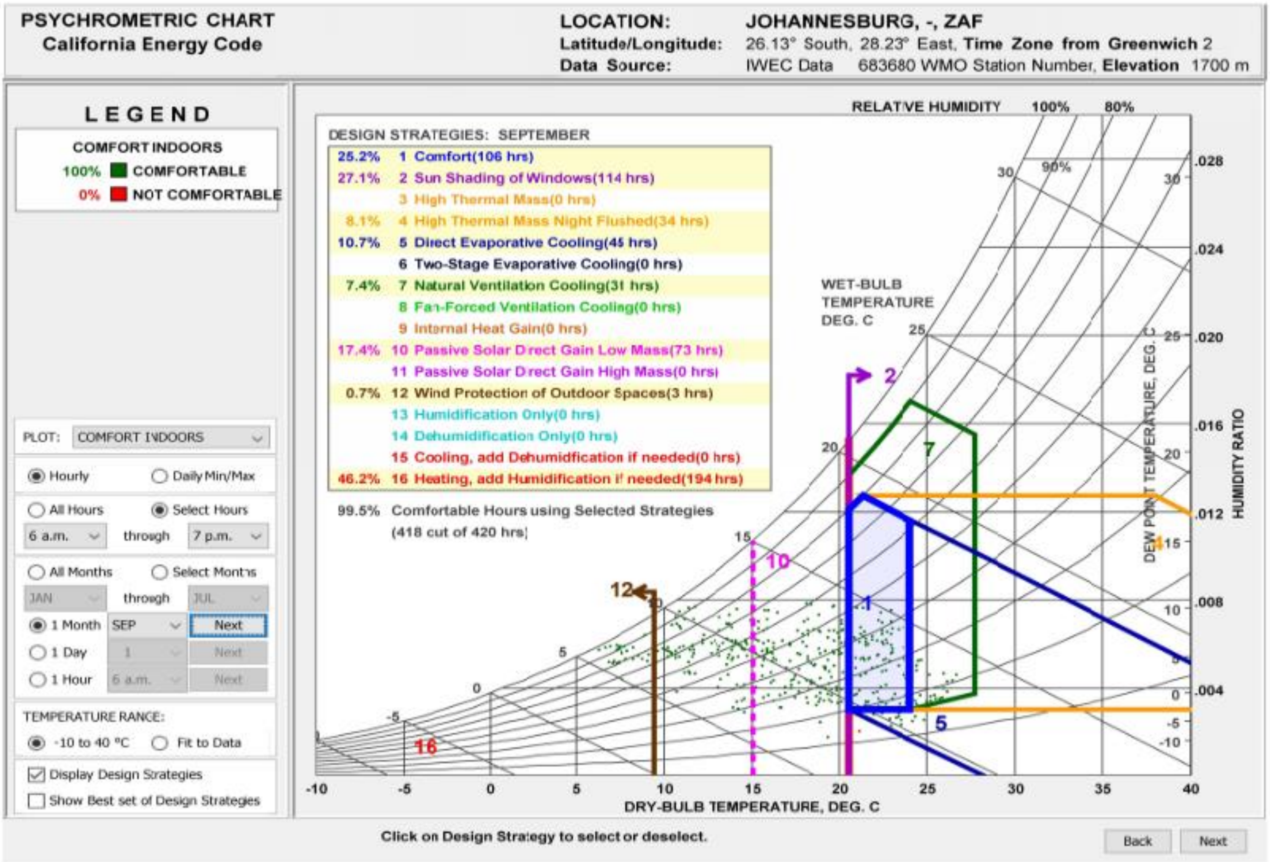
Psychrometric chart 1.7 – July



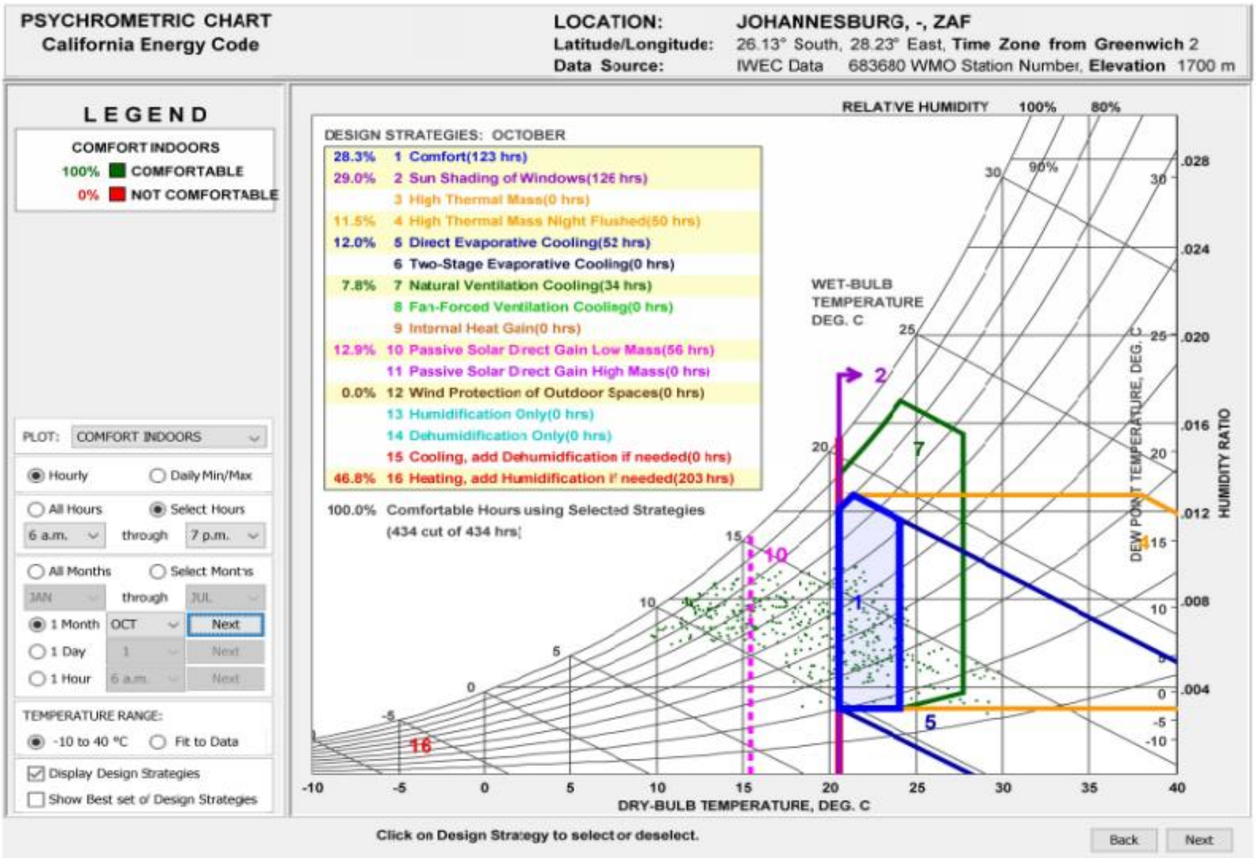
Psychrometric chart 1.8– August



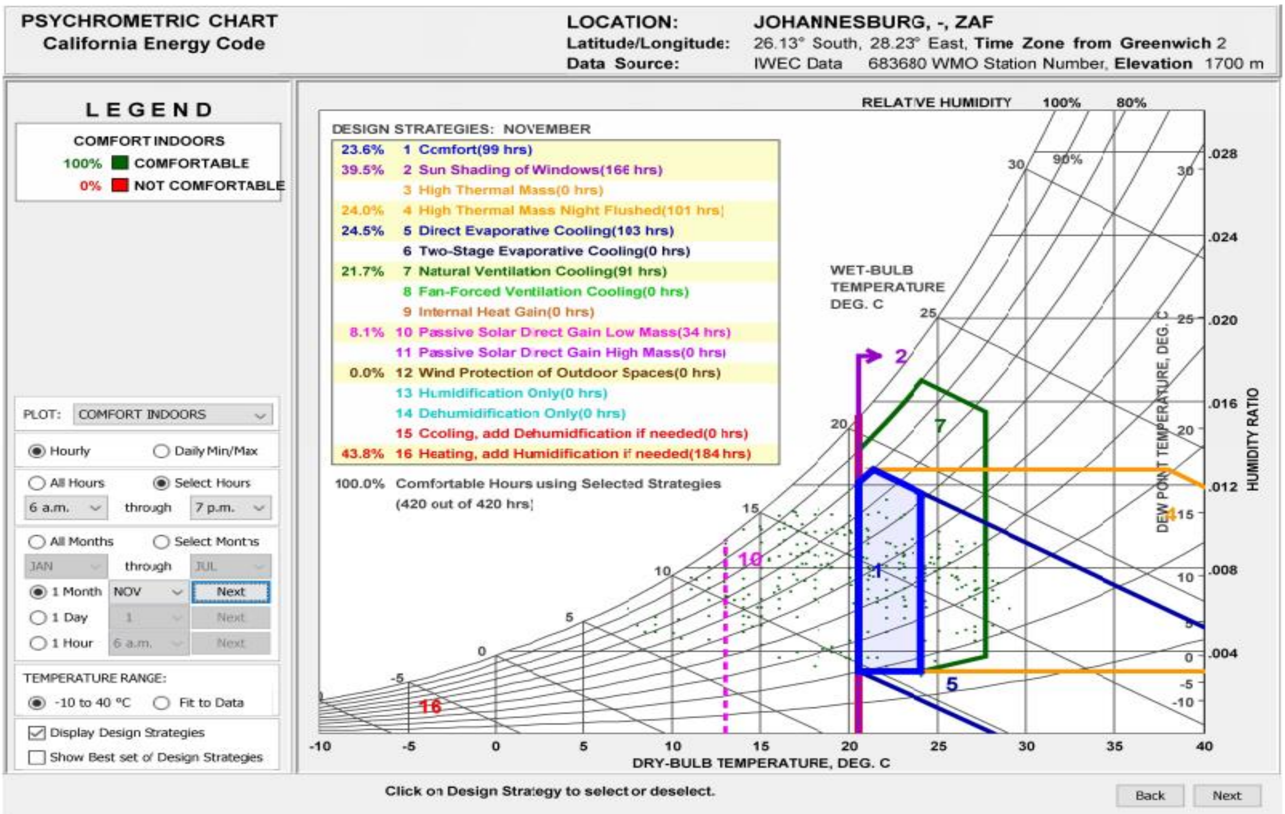
Psychrometric chart 1.9 – September



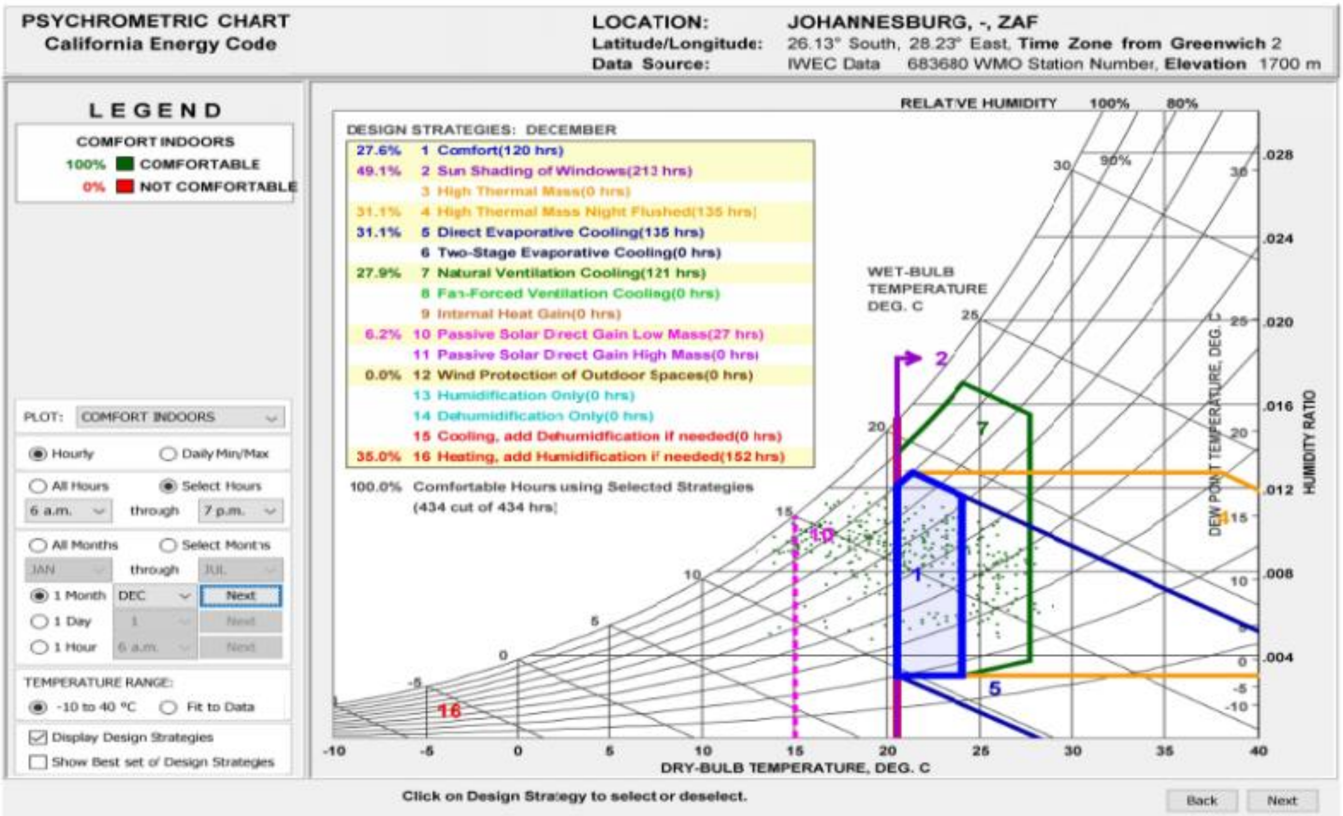
Psychrometric chart 1.10 October



Psychrometric chart 1.11 – November



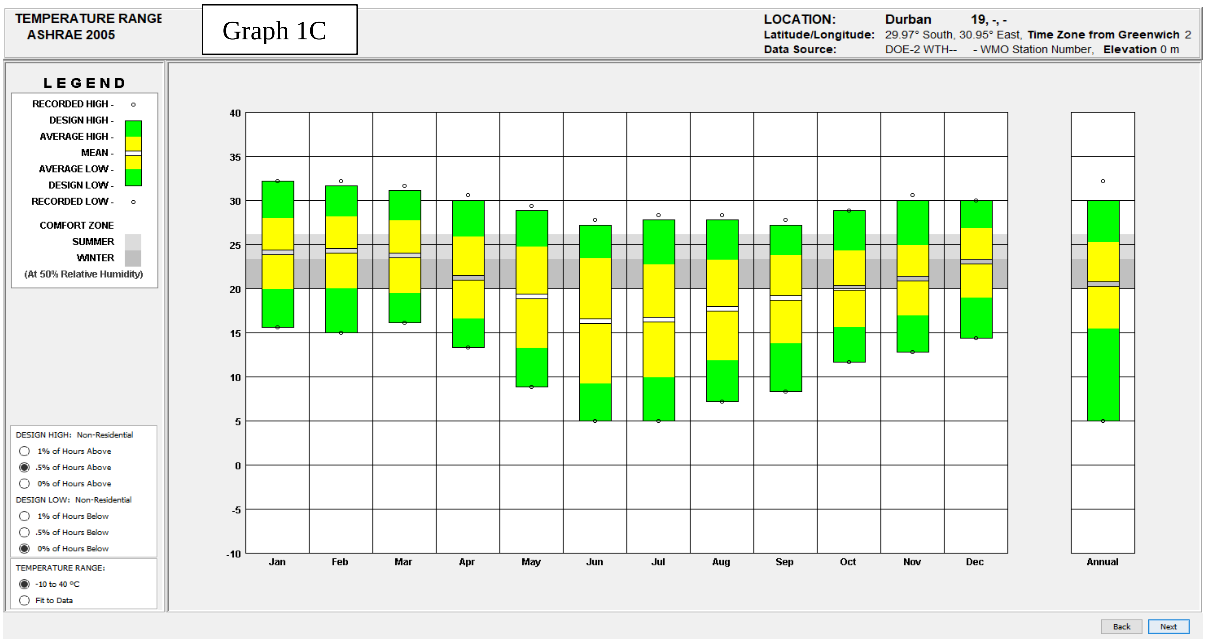
Psychrometric chart 1.12 – December

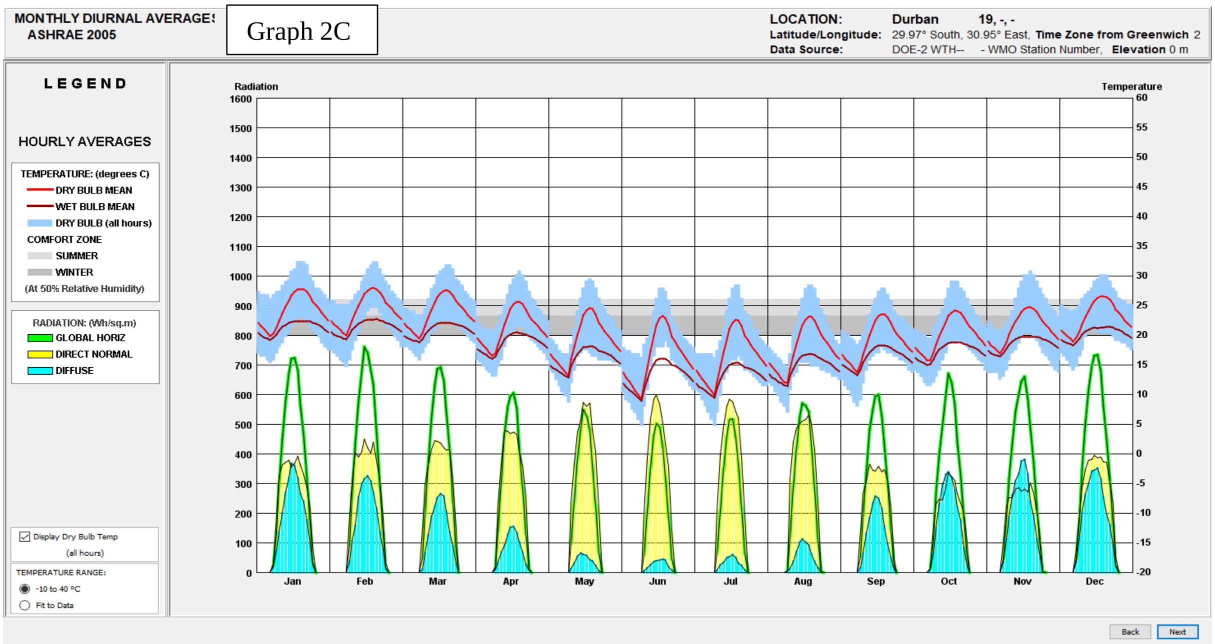


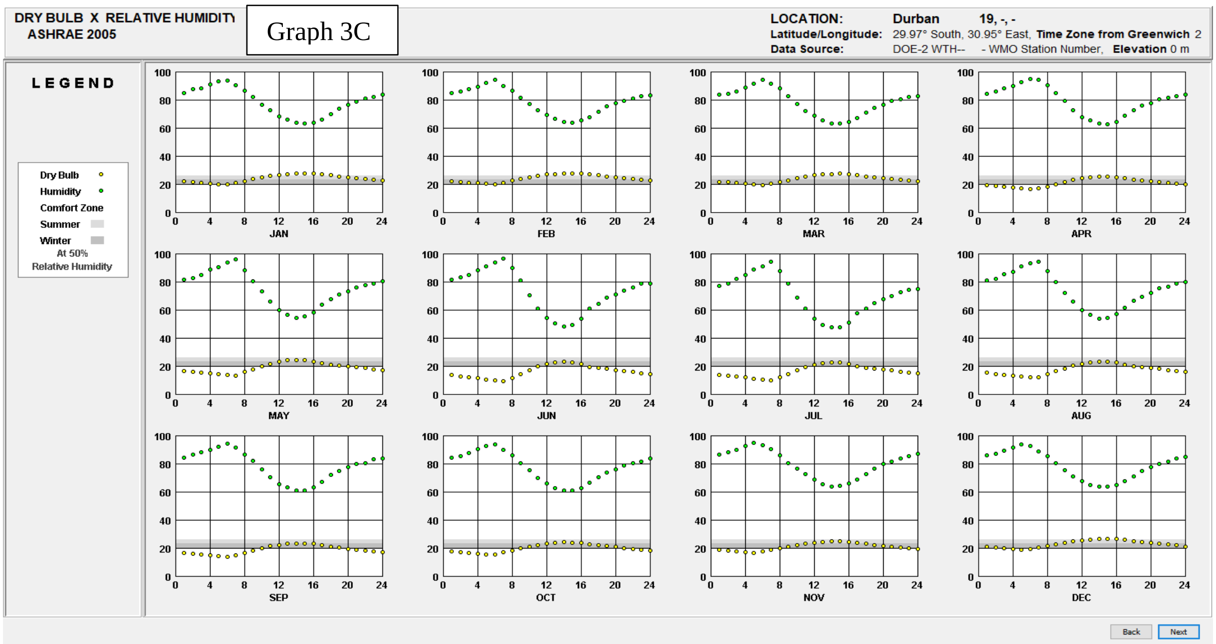
Appendix C

Climate analysis – Durban

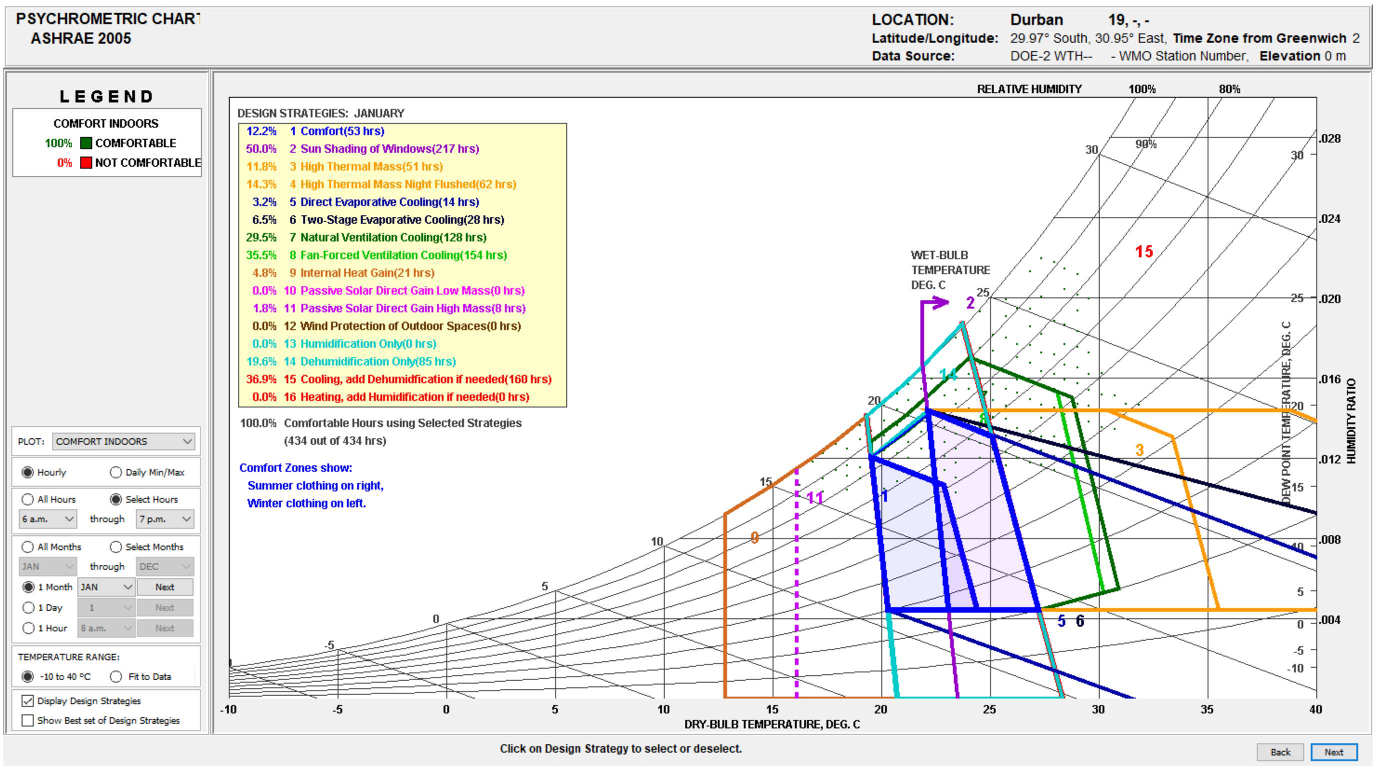
(Adapted from Climate Consultant-EnergyPlus software program)


TEMPERATURE RANGE
ASHRAE 2005
Graph 1C
LOCATION: Durban 19, -, -
Latitude/Longitude: 29.97° South, 30.95° East, Time Zone from Greenwich 2
Data Source: DOE-2 WTH-- - WMO Station Number, Elevation 0 m
LEGEND
RECORDED HIGH
DESIGN HIGH
AVERAGE HIGH
MEAN
AVERAGE LOW
DESIGN LOW
RECORDED LOW
COMFORT ZONE
SUMMER
WINTER
(At 50% Relative Humidity)
DESIGN HIGH: Non-Residential
1% of Hours Above
.5% of Hours Above
0% of Hours Above
DESIGN LOW: Non-Residential
1% of Hours Below
.5% of Hours Below
0% of Hours Below
TEMPERATURE RANGE:
-10 to 40 °C
Fit to Data
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Annual
Back
Next

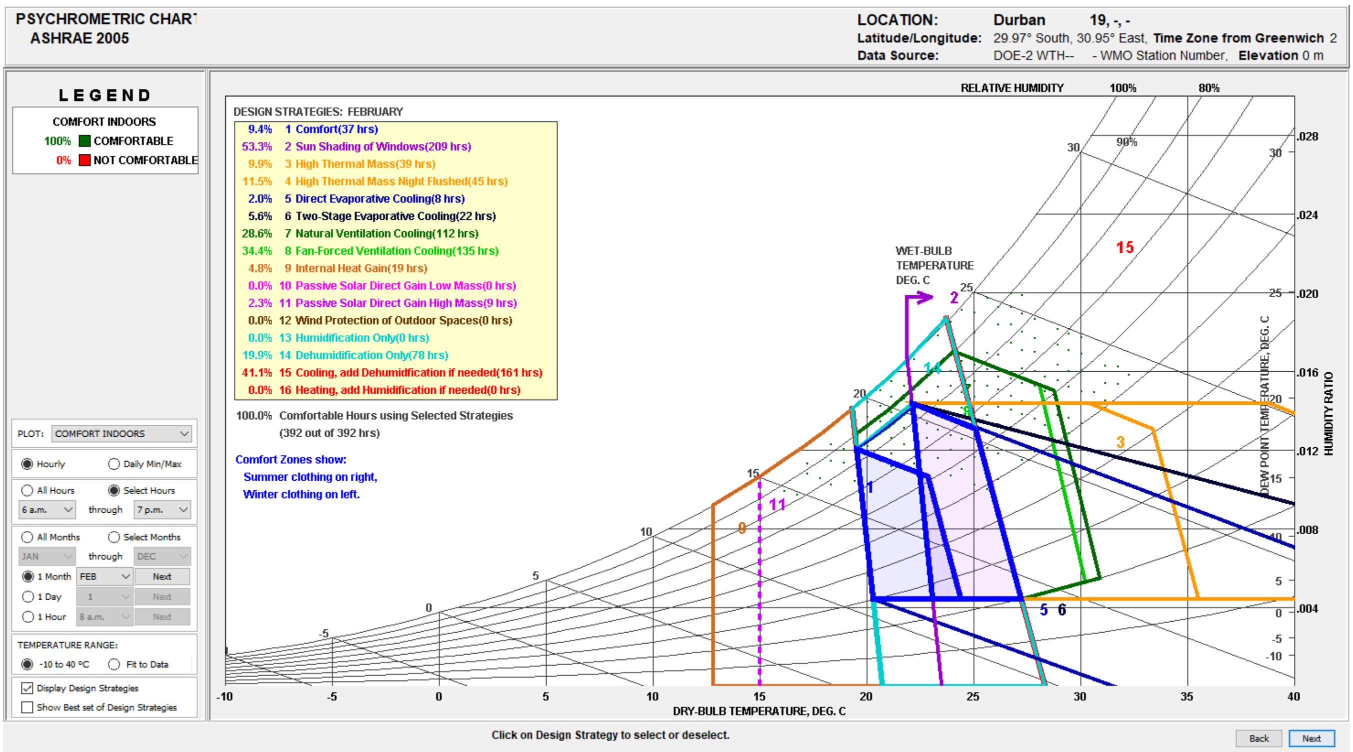

MONTHLY DIURNAL AVERAGES
ASHRAE 2005
Graph 2C
LOCATION: Durban 19, -, -
Latitude/Longitude: 29.97° South, 30.95° East, Time Zone from Greenwich 2
Data Source: DOE-2 WTH-- - WMO Station Number, Elevation 0 m
LEGEND
HOURLY AVERAGES
TEMPERATURE: (degrees C)
DRY BULB MEAN
WET BULB MEAN
DRY BULB (all hours)
COMFORT ZONE
SUMMER
WINTER
(At 50% Relative Humidity)
RADIATION: (Wh/sq.m)
GLOBAL HORIZ
DIRECT NORMAL
DIFFUSE
Display Dry Bulb Temp (all hours)
TEMPERATURE RANGE:
-10 to 40 °C
Fit to Data
Radiation
Temperature
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Back
Next


DRY BULB X RELATIVE HUMIDITY
ASHRAE 2005
Graph 3C
LOCATION: Durban 19, -, -
Latitude/Longitude: 29.97° South, 30.95° East, Time Zone from Greenwich 2
Data Source: DOE-2 WTH-- - WMO Station Number, Elevation 0 m
LEGEND
Dry Bulb
Humidity
Comfort Zone
Summer
Winter
At 50% Relative Humidity
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
Back
Next

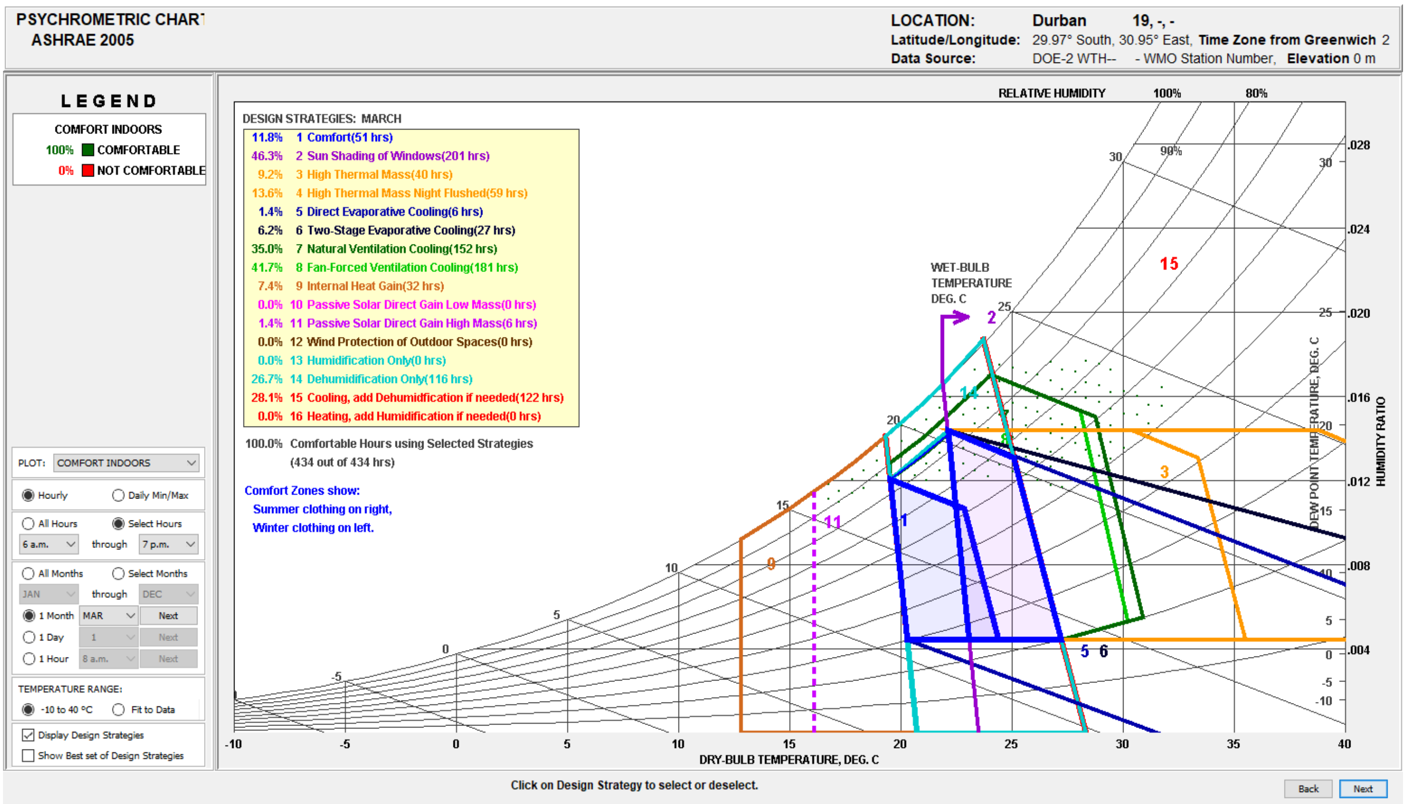
Psychrometric chart 2.1 – January



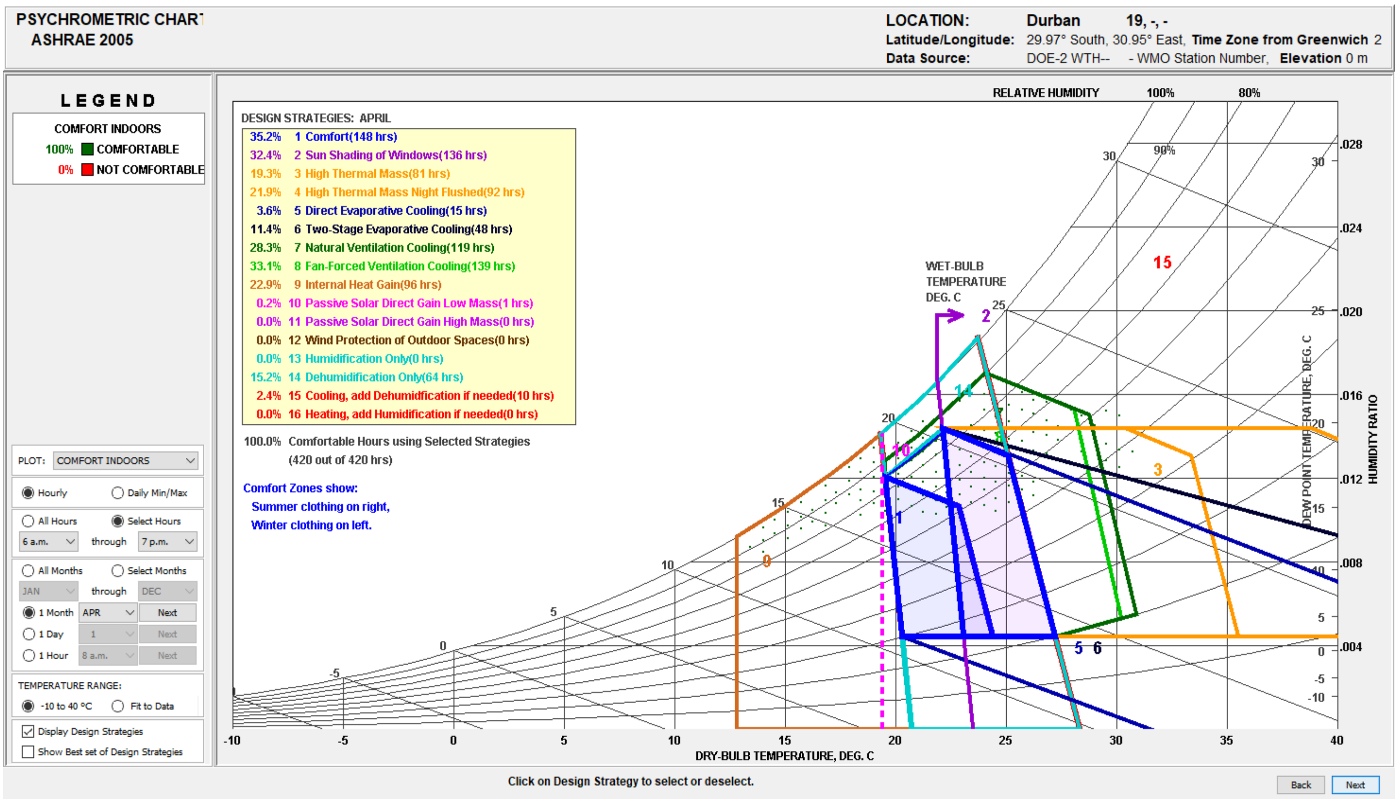
Psychrometric chart 2.2 – February



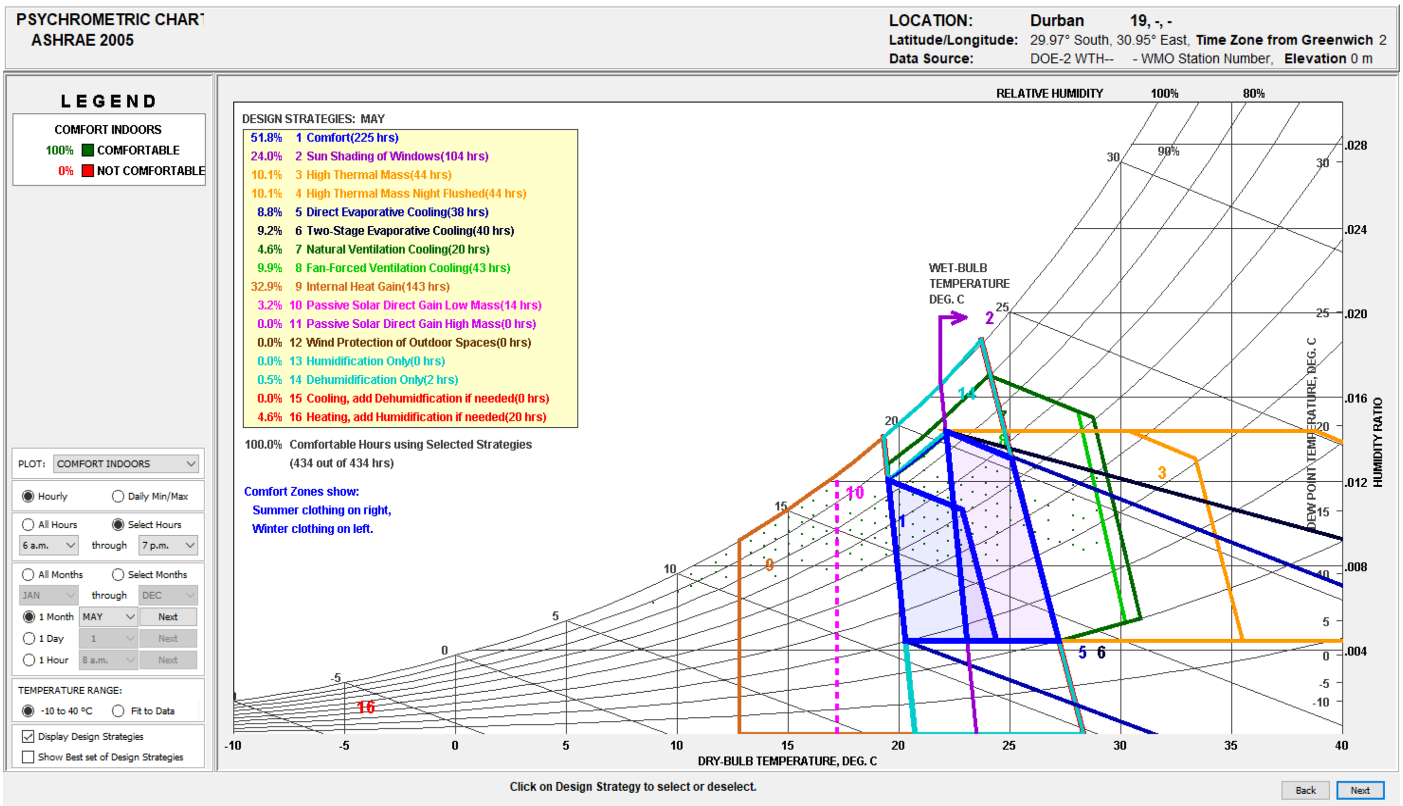
Psychrometric chart 2.3 – March



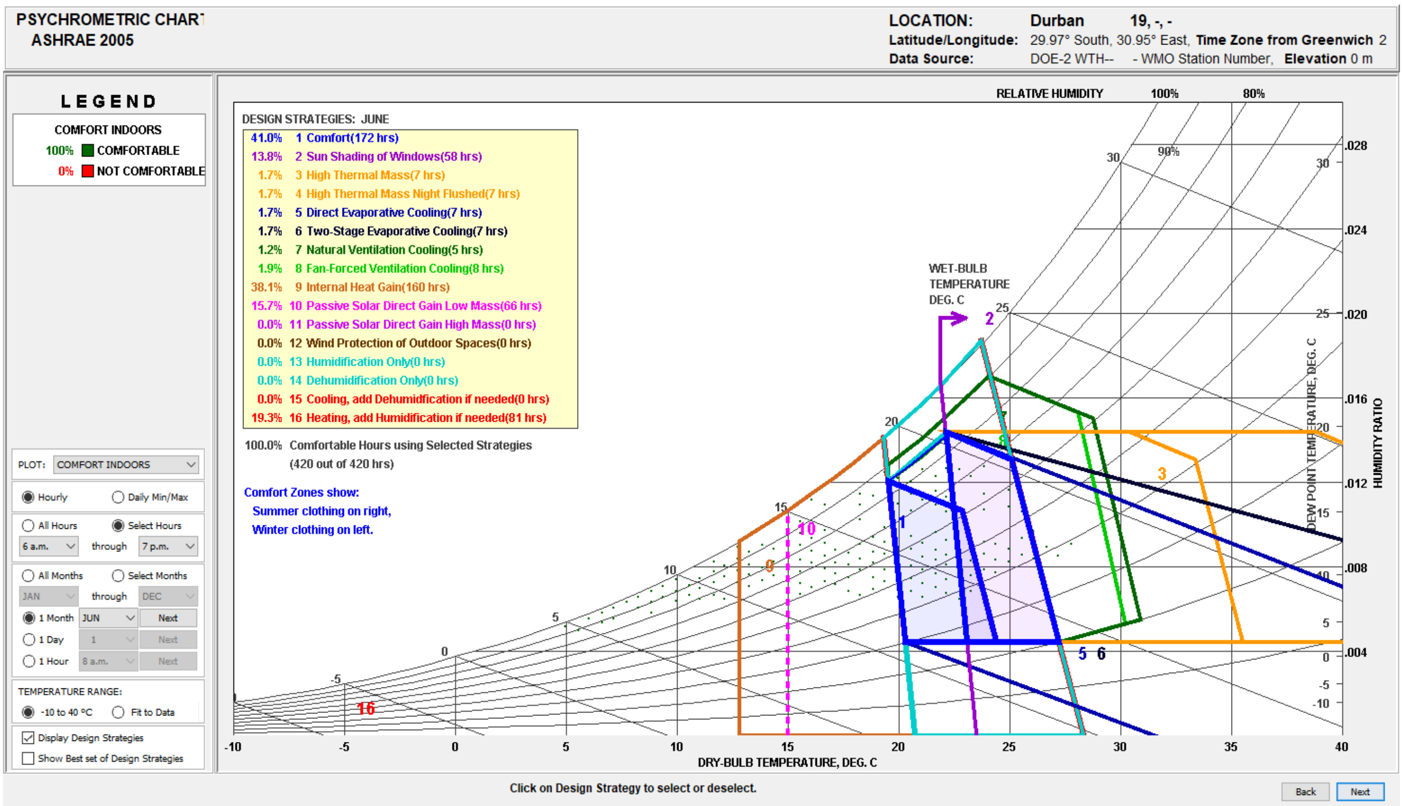
Psychrometric chart 2.3 – April



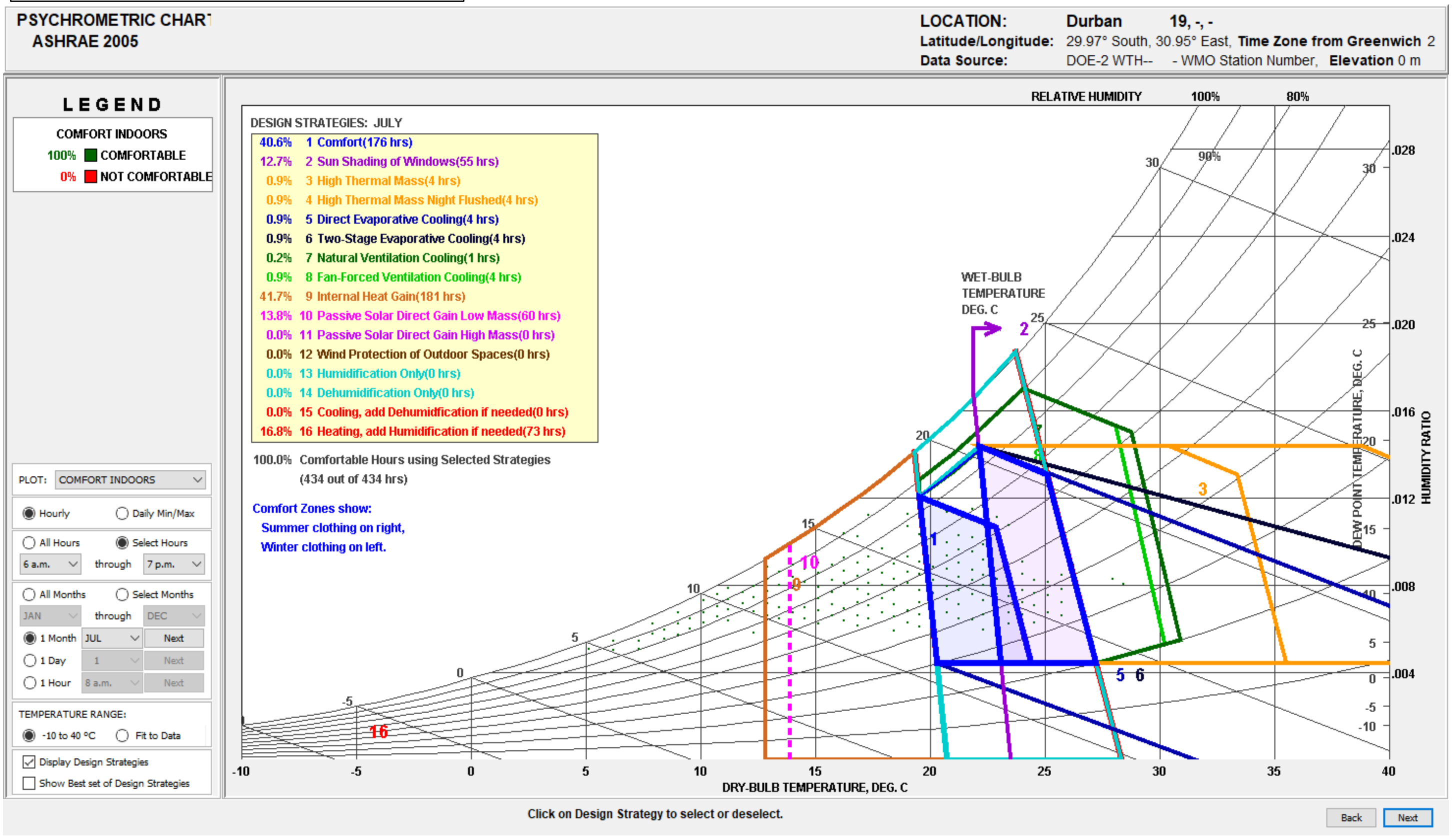
Psychrometric chart 2.5 – May



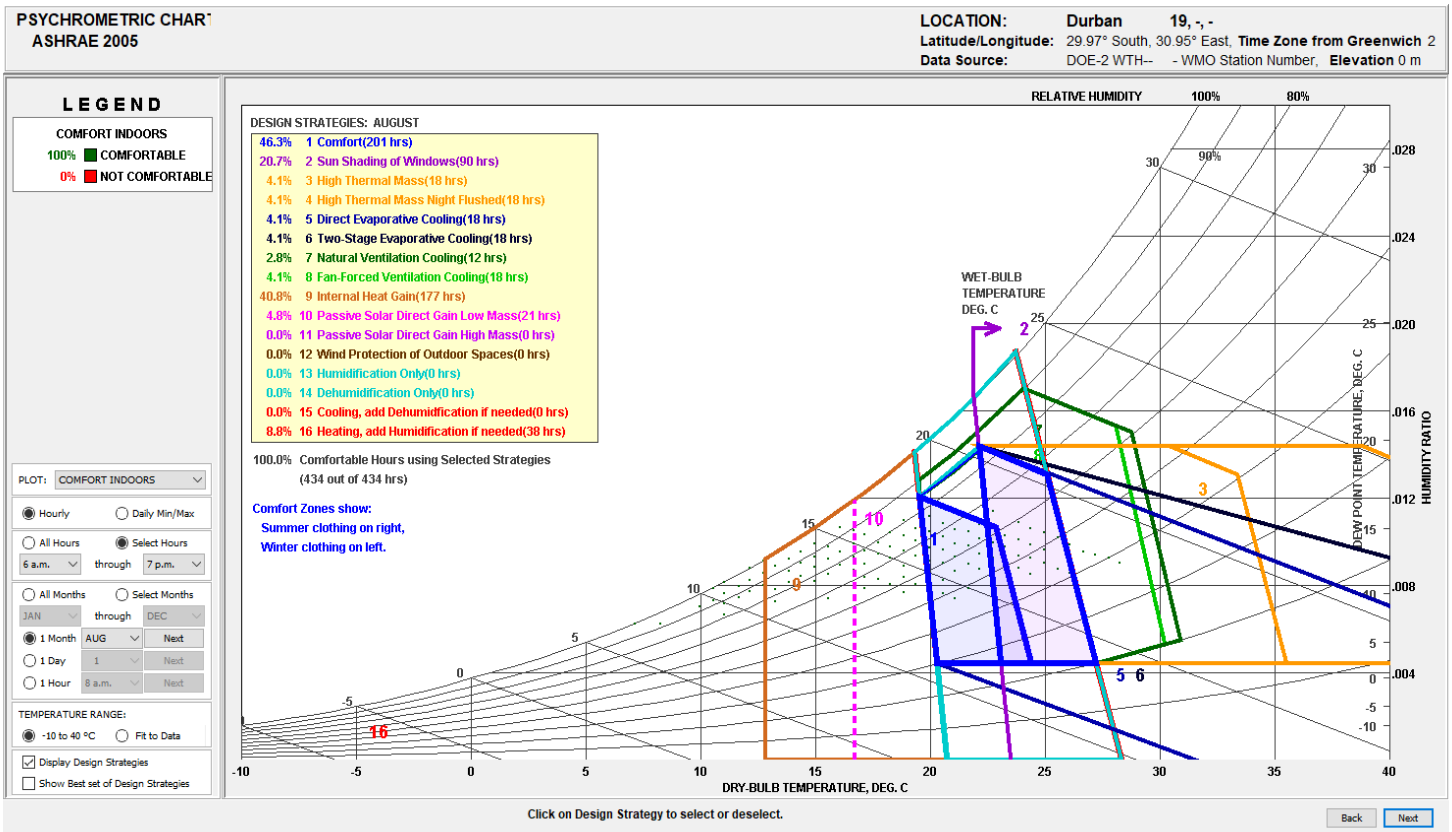
Psychrometric chart 2.6 – June



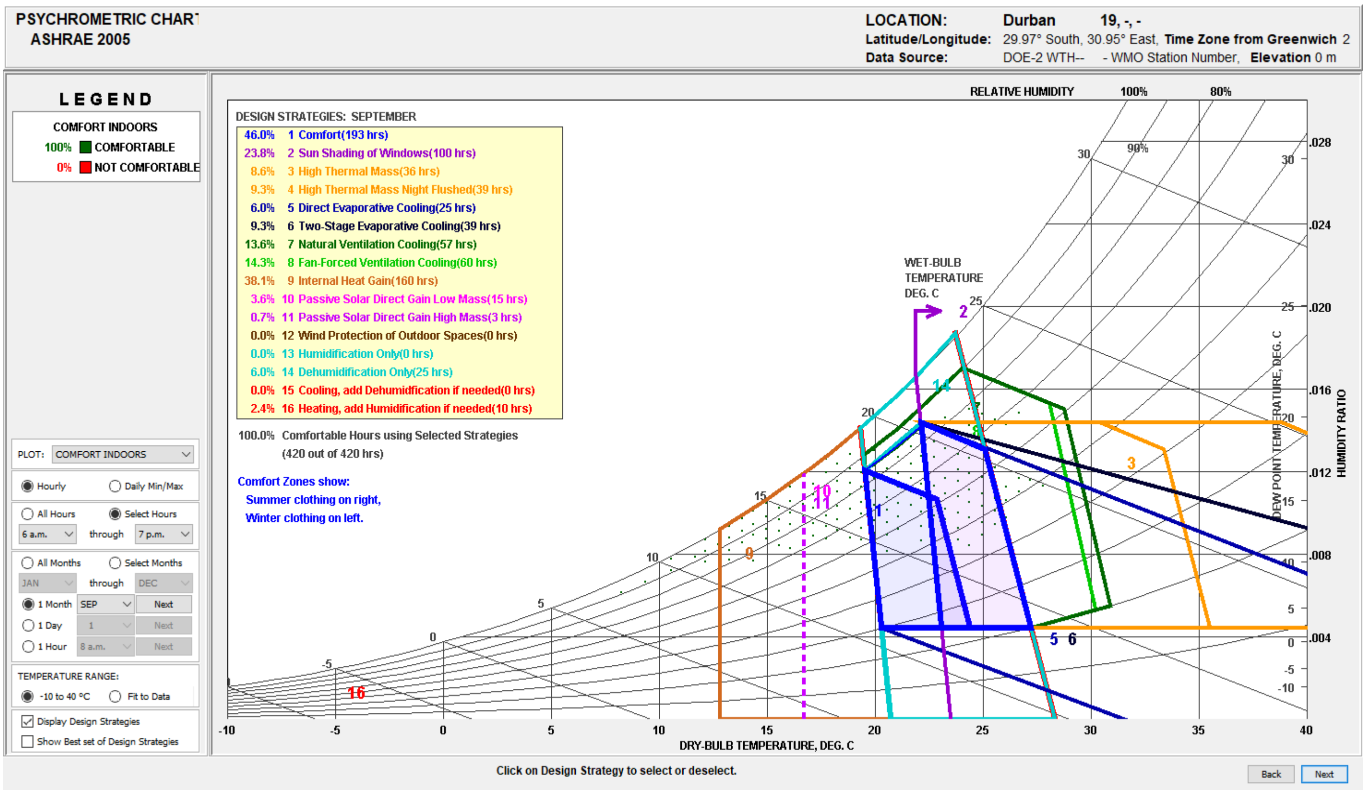
Psychrometric chart 2.7 – July



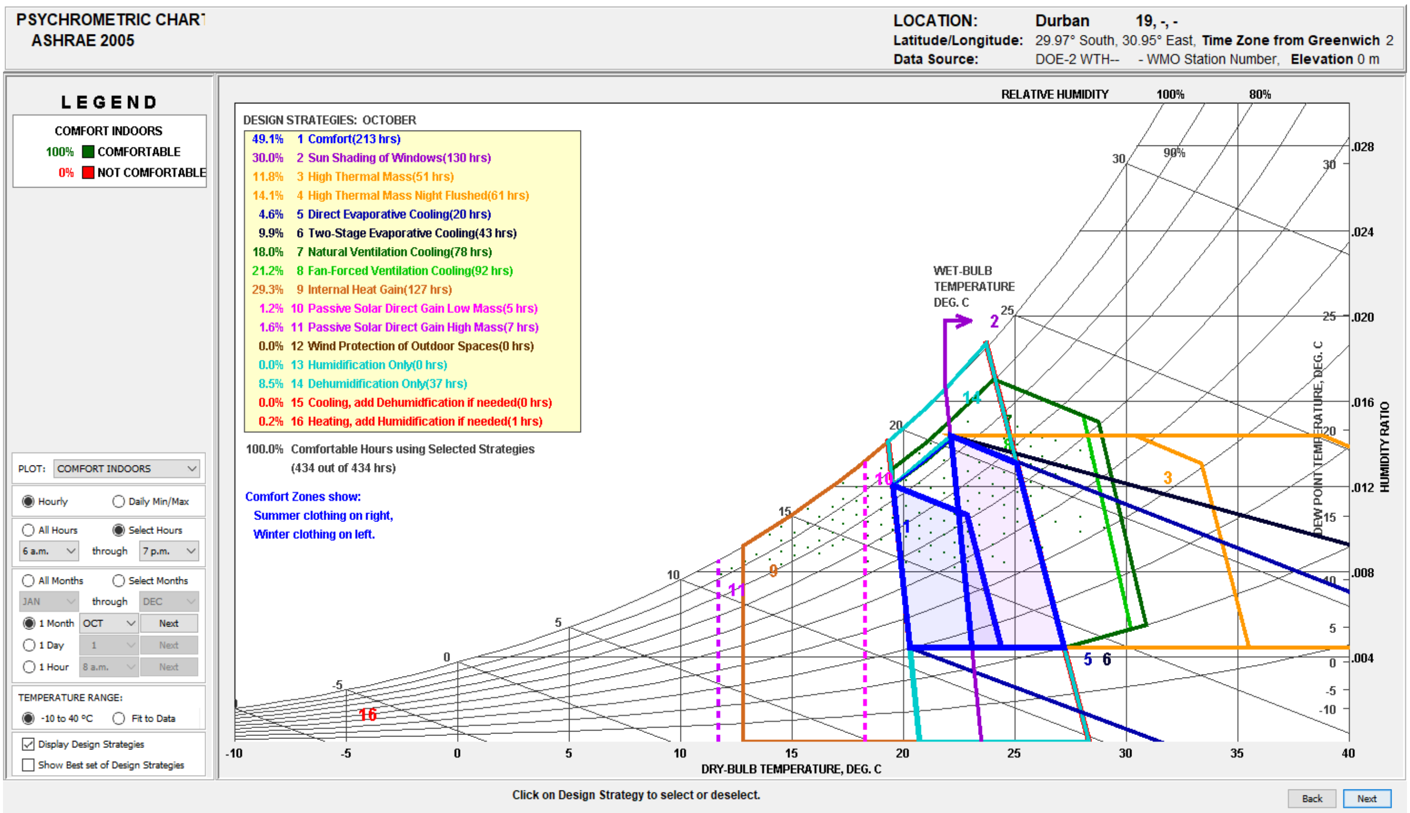
Psychrometric chart 2.8 – August



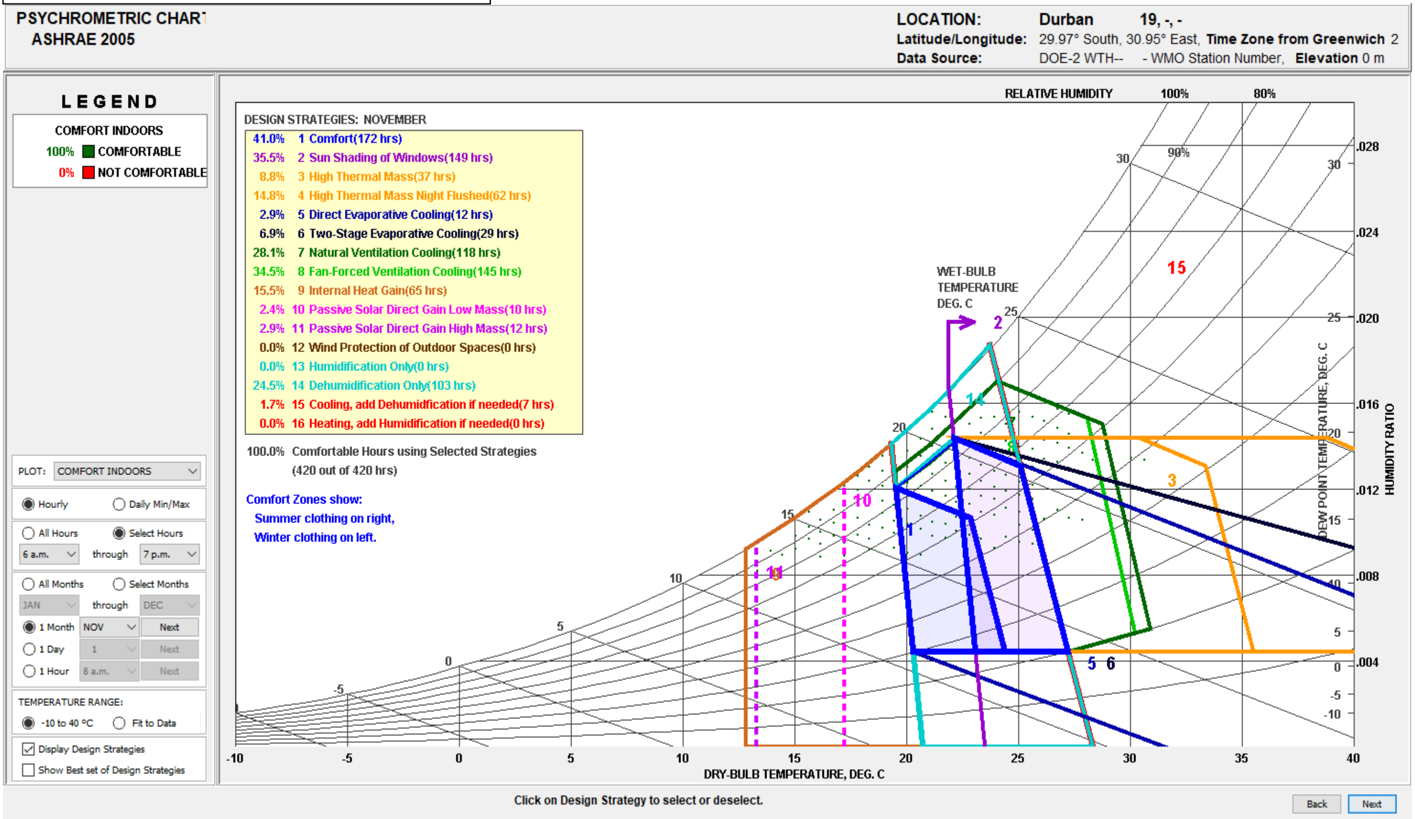
Psychrometric chart 2.9 – September



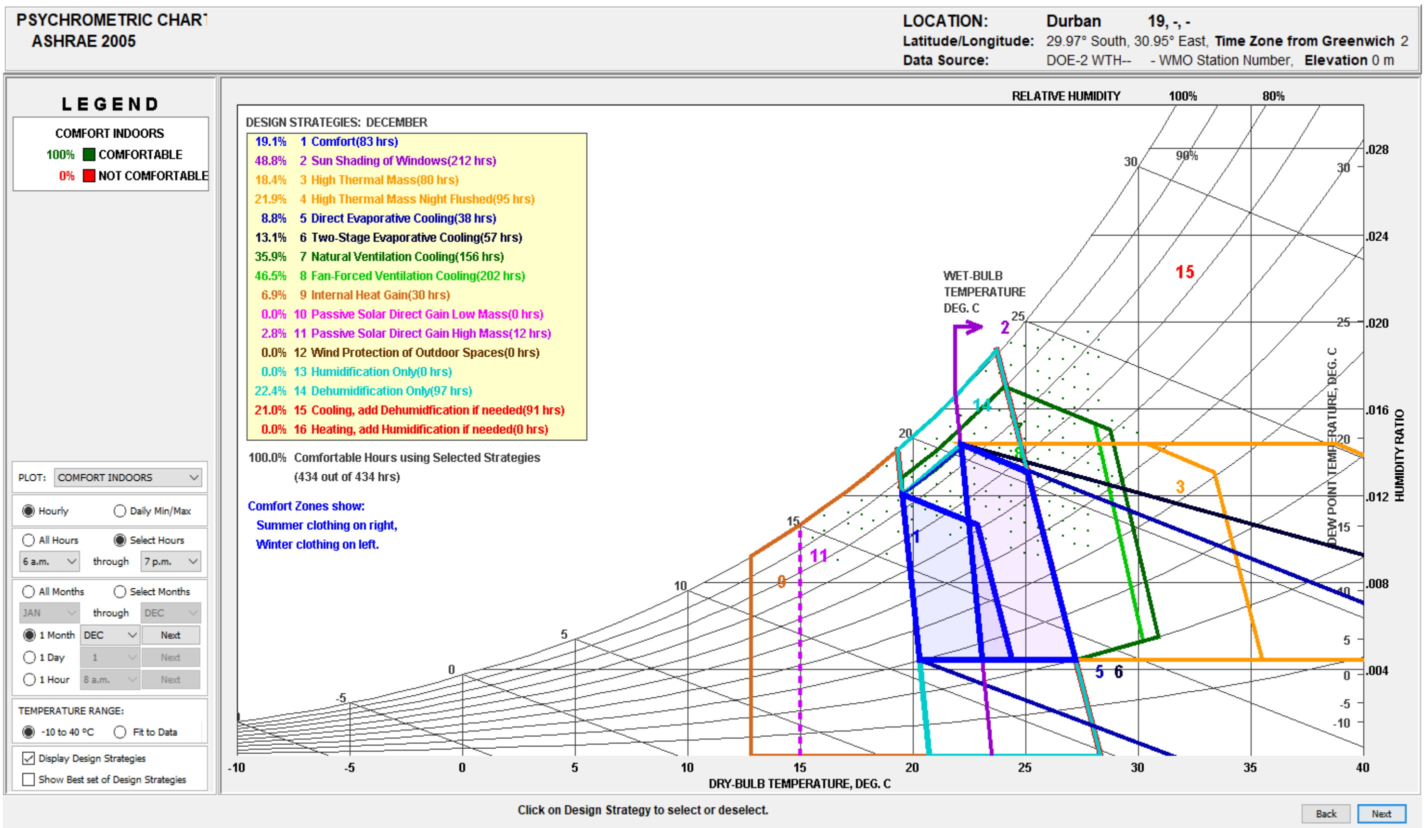
Psychrometric chart 2.10 – October



Psychrometric chart 2.11 –November



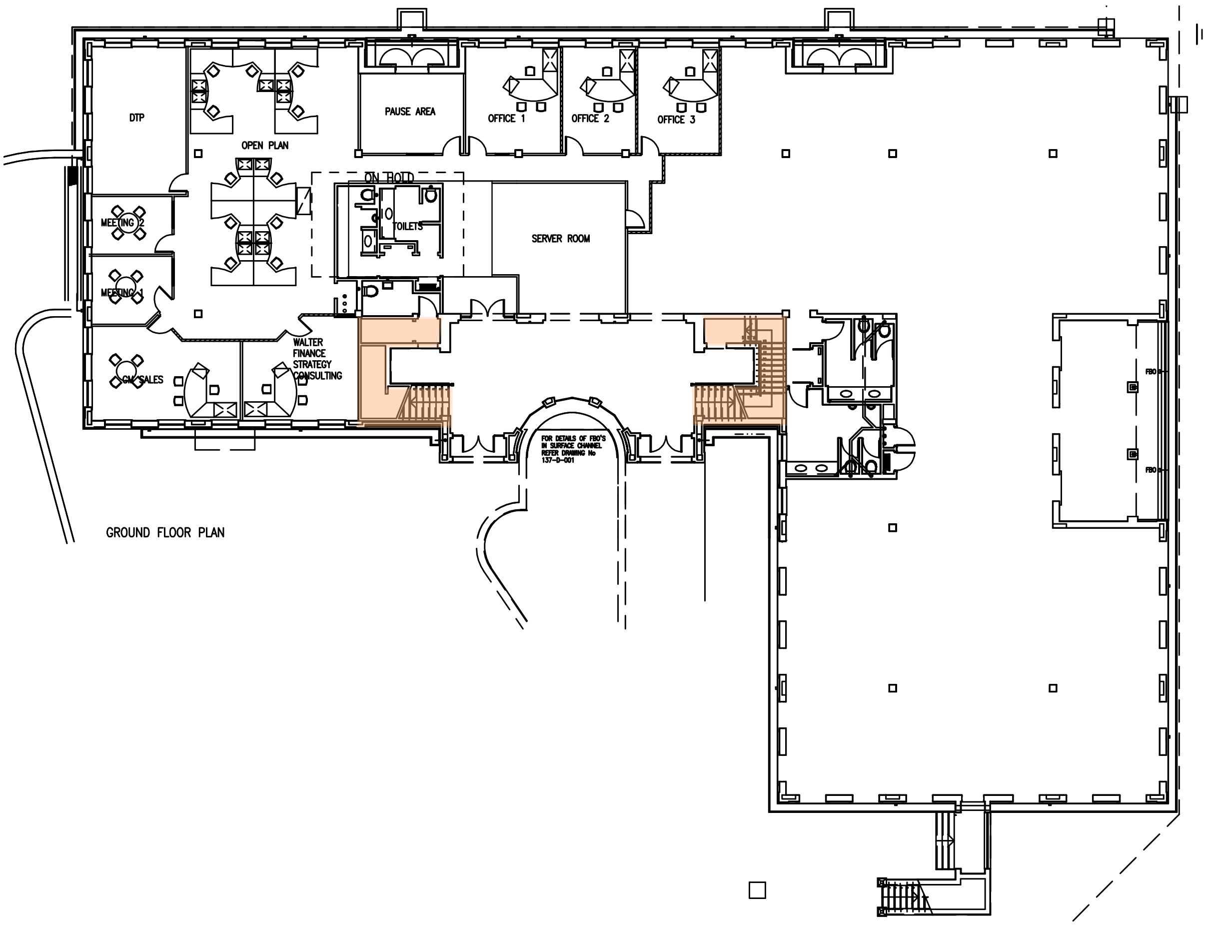
Psychrometric chart 2.12 –December



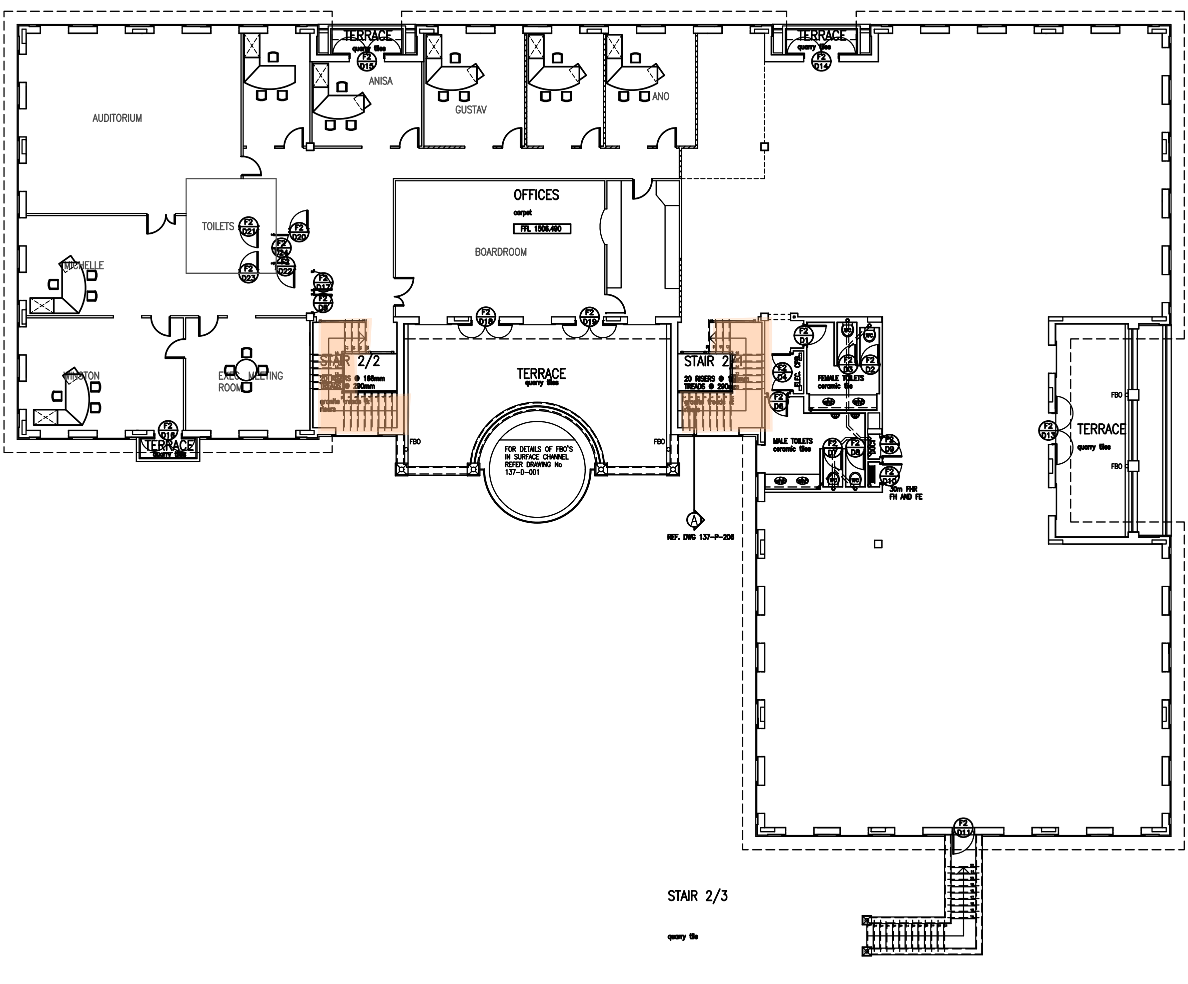
Appendix D

Case study building plans (Adapted from building owners drawing records)

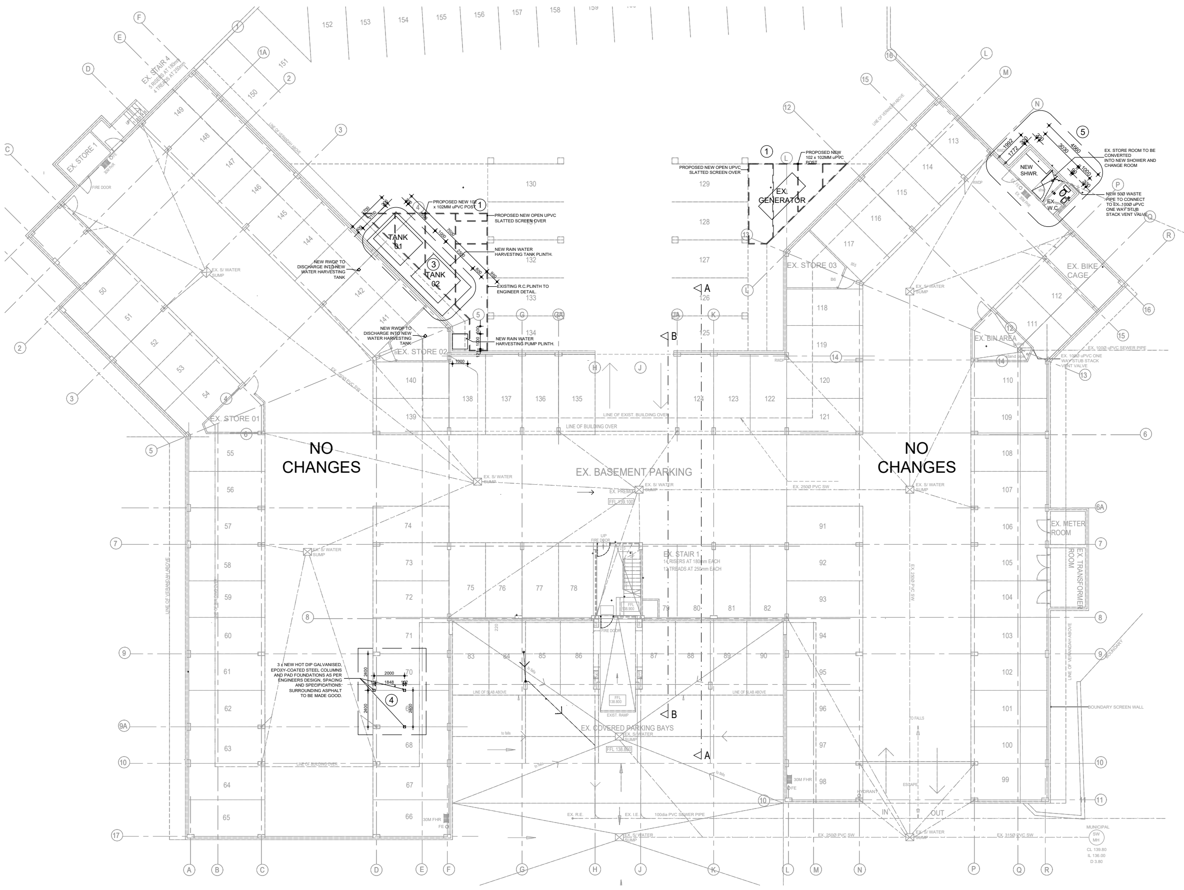
The Planes Building: Ground floor plan



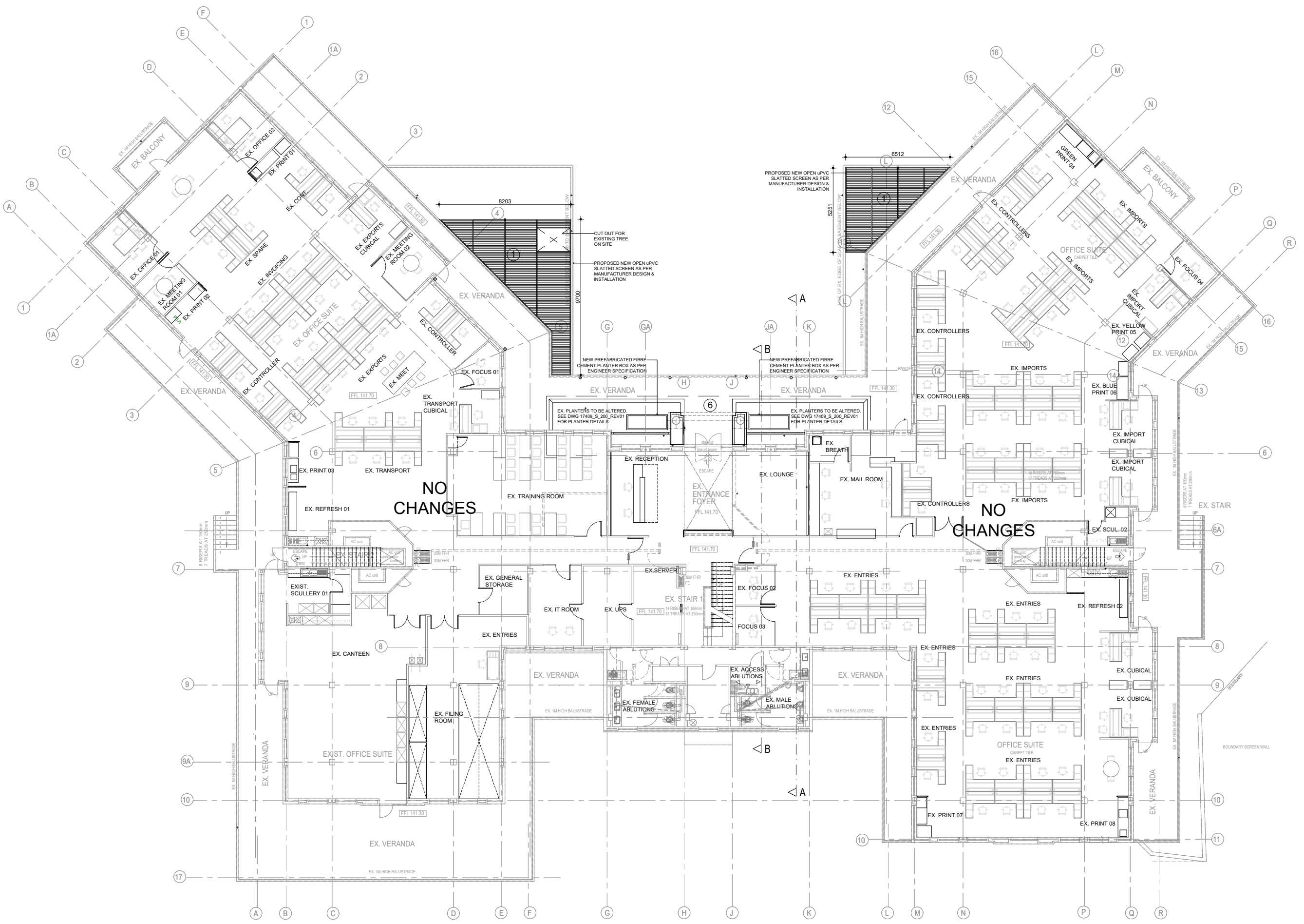
The Planes Building: First floor plan



Frosterley Crescent : Basement floor plan



Frosterley Crescent : Ground/first floor plan



Appendix E

Ethics clearance certificate

SCHOOL OF ARCHITECTURE AND PLANNING
HUMAN RESERCH ETHICS COMMITTEE

CLEARANCE CERTIFICATE

PROTOCOL NUMBER: SOAP077/09/2018

PROJECT TITLE:	How the dual role of concrete elements as structural systems and thermal mass can be adapted and optimised towards energy efficiency for office buildings under different climate zones of South Africa
INVESTIGATOR/S:	Pooja Mistry (Student No: 444273)
SCHOOL:	Architecture and Planning
DEGREE PROGRAMME:	Masters in Sustainable and Energy Efficient (MSEEC)
DATE CONSIDERED:	17 October 2018
EXPIRY DATE:	17 October 2019
DECISION OF THE COMMITTEE:	Approved

CHAIRPERSON ______________________
(Professor Daniel Irurah)

DATE: 17- 10 - 2018

cc: Supervisor/s: Daniel Irurah

DECLARATION OF INVESTIGATORS

I/We fully understand the conditions under which I am/we are authorized to carry out the abovementioned research and I/we guarantee to endure compliance with these conditions. Should any departure to be contemplated from the research procedure as approved I/we undertake to resubmit the protocol to the Committee.

Signature pp. P Mistry **Date** 23 - 10 - 2019

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