EFFECT OF WALLING MATERIALS' THERMAL TRANSMITTANCE AND THERMAL MASS ON INDOOR THERMAL COMFORT IN NAIROBI

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Effect of Walling Materials' Thermal Transmittance and Thermal Masson Indoor Thermal Comfort in Nairobi

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DECLARATION

This thesis is my original work and has not been presented for a degree in any other University

Signature………………………………Date....……………………..

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This thesis has been submitted for examination with our approval as University supervisors

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DEDICATION

This work is dedicated to sons Jay Kariuki and Mash Kamau

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ABBREVIATIONS AND ACRONYMS

ASHRAE	Society of Heating, Refrigeration and Air Conditioning Engineers
CEN	European Committee for Standardization
CIBSE	Chartered Institute of British Services Engineers
DhC	Degree-hours criterion
EPS	Expanded Polystyrene
SIP	Structural Insulated Panel
IEA	International Energy Agency
IEEC	International Energy Conservation Code
ISO	International Organization for Standardization
NHC	National Housing Corporation
SANS	South African National Standard
VHC	Volumetric Heat Capacity

ABSTRACT

The control of indoor thermal environment in buildings is necessary for occupants' health and comfort. A study was undertaken to develop the criteria for the selection of walling materials for thermal comfort in residential buildings in Nairobi, Kenya. Indoor and outdoor temperature was monitored in three buildings with different walling materials. Natural stone, timber and expanded polystyrene (EPS) walls were considered. Using the Autodesk Ecotect 2011 thermal simulation software, different scenarios were simulated. Input data included the spatial dimensions of the buildings, climatic data (air temperature, relative humidity and solar radiation), construction materials, human activities within the buildings, clothing worn, indoor relative humidity and heat output of domestic equipment. In the simulation model, the effect of thermal transmittance and thermal mass of different walling materials on indoor thermal comfort was studied. Materials considered in the simulation included natural stones, galvanized iron sheets, concrete, fired clay, stabilized earth, timber and expanded polystyrene panels (EPS). In all cases the indoor temperature was higher than the outdoor temperature. The observed mean indoor temperature of the living room was 3.8 ^{o}C, 3.3 ^{o}C and 2.5 ^{o}C above the mean outdoor temperature for the EPS, timber and stone wall buildings, respectively. The simulation showed that thermal transmittance of walls had a more significant effect on thermal discomfort compared to thermal mass. Thermal discomfort in the buildings was found to have a direct linear relationship with thermal transmittance of the walls. To avoid thermal discomfort, thermal transmittance of walls should not exceed 0.70W/m^{2}K.

Key words: thermal comfort, thermal mass, thermal transmittance, walling materials

CHAPTER ONE
INTRODUCTION

1.1 Background

Buildings accommodate people and provide shelter to protect them from the weather elements, provide security and privacy. Walls, which normally form the largest surface area of the building envelope, control variations in external temperatures by through insulation and heat storage. Provision of suitable indoor environmental quality is required for sustainable buildings. With people in modern societies spending about 90% of their time indoors (Leech *et al.*, 2002), it is necessary that indoor thermal environmental quality is considered in building design for health, comfort, energy efficiency and productivity (Seppänen*et al.*, 2005).

Thermal comfort is defined as that condition of mind, which expresses satisfaction with the thermal environment (ISO 7730, 2006). The parameters that determine thermal comfort include air temperature, mean radiant temperature, humidity, air velocity and personal variables including clothing and the metabolic rate of an individual. Various standards such as ASHRAE Standard 55(2010) and the International Standard ISO 7730 (2006) have been developed to determine the right combination of these factors to ensure thermal comfort. These factors may be achieved by passive design to control the thermal environment in buildings through natural process without artificial heating and ventilation (Beggs, 2007). Passively designed buildings run with a minimum of energy input.

Various heat exchange processes take place between a building and the external environment. Solar heat flows by conduction through various building elements such as walls, roof and floors. Other than conduction, heat also flows by convection and radiation at the surfaces. In addition to solar heat, buildings also receive heat from human metabolic activities. The human body continuously produces heat, part of which is used as work, while the rest is dissipated into the environment (Havenith, Holmer& Parsons, 2002). Part of the heat energy is stored in the building fabric. This flow and storage of heat depends on the thermo-physical properties of the building materials.

The main properties of the materials that determine the rate of the heat exchange are thermal transmittance (U-value) and thermal mass. Materials may be lightweight with low thermal conductivity for insulation or dense with high thermal mass for collecting, storing and releasing solar heat when needed especially at night. In Nairobi, Kenya, the main materials used for walling have a wide range of thermal properties. Natural Stone and earth have high thermal transmittance values and high thermal mass while galvanized iron sheets and timber have very low thermal mass. Recently structural insulated prefabricated panels (SIPs) consisting of two outer layers of structural facing material separated by an insulated core of polymer foam have been introduced in Kenya. These panels have very low thermal transmittance and thermal mass (ISO 10456, 2007).

Previous studies of thermal performance of different walling materials in Australia, Yemen, Turkey and Cameroon show that their performance on regulating indoor temperature differ (Heathcote & Moor, 2007, Alhaddad & Jun, 2013, Elias-Ozkan et al., 2006, Kemanjou & Mb, 2012). They, however, seem to suggest that high thermal mass materials perform better than lighter insulating materials in regulating indoor temperature in areas with high diurnal temperature range. For Nairobi, Kenya, in the sub-tropic highland climatic zone, during the months of June to August, low temperatures occur during the night and early morning with values as low as 8° C or even 6° C recorded(Kenya Meteorological Services, 2015).

The relationship between thermal properties of building materials and the indoor thermal environment forms a basis for building regulations in many countries around the world.For example, in the United Kingdom and Japan the regulations specify maximum thermal transmittance values for walls (The Building Regulations, 2010, IEA, 2008). In South Africa, the standards incorporate both the thermal mass and thermal transmittance of materials for walling (SANS 204, 2011).

On the other hand, in Kenya, building materials for design and construction of building walls are regulated by the Local Government (Adoptive By-Laws) Building Order (1968).The third schedule of the By-Law tabulates minimum thicknesses of stone, brick and blocks depending on height and length of walls for structural stability and crushing strength and therefore not appropriate for regulation of a healthy and energy efficient built environment. Other materials are not mentioned in the By-Law(Ministry of Local Government, 1969).

1.2 Problem Statement

The building regulations for walls in Kenya (Local Government (Adoptive By-Laws) Building Order 1968)are inadequate as they are concerned with structural stability only and do not specify requirements for a comfortable indoor thermal environment. Kenya’s Building Code does not include the required thermo-physical properties of building materials to guide architects and engineers in material specification within the local climatic conditions. It is also not possible to determine suitability of materials imported into or developed by researchers in the country. In the highland areas of Kenya temperatures fall to mean minimum values below 11°C during the cold months of June to August (Kenya Meteorological Services, 2015). Such low temperatures have been associated with respiratory diseases and mortality. The basis of material specifications in Kenya has lagged behind international trends which provide performance requirement for thermal quality and energy efficiency. The purpose of the study is to establish the properties of walling materials that are suitable for building in Nairobi for thermal comfort.

1.3 Objectives

1.3.1 General Objective

To develop thermal performance design criteria for the selection of building materials for walls in residential houses in Nairobi, Kenya.

1.3.2 Specific Objectives

1. To compare the effects of natural stone walling, timber frame walling and insulated walling panels on indoor air temperatures in residential buildings in Nairobi, Kenya.
2. To determine the relationship between the thermo-physical properties of walling materials and indoor thermal conditions in residential buildings in Nairobi, Kenya.

1.4 Hypotheses.

1.4.1 Alternative Hypothesis (Ha)

There is a relationship between thermo-physical properties of building materials and the indoor thermal quality.

1.4.2 Null Hypothesis (H_o)

There is no relationship between thermo-physical properties of building materials and the indoor thermal quality.

1.5 Research Significance

This research is carried out in a cool sub-tropic highland climatic zone that is normally associated with moderate temperatures throughout the year. Most studies of indoor thermal environments are carried out in areas of extreme climatic conditions: cold temperate, hot humid or hot dry areas. Few studies in human thermal environments have been carried out in Africa. One of the most extensive studies of thermal comfort studied four continents: North America, Europe, Asia and Australia, significantly leaving out Africa (De Dear & Brager, 2002).

Raw and Oseland (1994) lists five advantages of knowledge of thermal comfort research: guiding the design of buildings, improving internal air quality, promoting good health, reducing the production of carbon dioxide and increasing the work efficiency of the building occupants. These advantages are also relevant to people in this part of Africa.

In Kenya, the research in building materials for walls has for a long time concentrated on earth materials which are traditional, available and have high thermal mass as alternatives to natural stone. However, lightweight insulating building materials such as timber and structural insulated prefabricated panels may offer alternatives for thermal control as well as increasing the speed of construction. The research will provide insights into the relative importance of insulation versus thermal mass for buildings in tropical highland climates.

The findings of this research will contribute by filling a gap due to the inadequacy of the building code in Kenya. The Local Government (Adoptive By-Laws) Building Order (1968) has no provision for determination of the appropriate thermal properties of building materials or building elements.

1.6 Research Justification

Sustainable building construction requires architects and engineers to create healthy environments that improve the living standards of residents and reduce exposure to physical risk (Halliday, 2008). Indoor temperatures are a significant factor in ensuring that this condition is met in buildings. The temperature condition in Nairobi is such that the mean annual temperature is17.7˚C and the mean monthly temperature is 15.5^{o}C in July, the coldest month. These temperatures are below the optimal range of 20˚C to 23˚C outdoor temperatures that will minimise the need for indoor temperature adjustment (Humphreys, 1995). This suggests requirement for some measures of intervention to ensure that higher temperatures are maintained in buildings.

Low and high temperature have been related to respiratory diseases (Mourtzoukou & Falagas, 2007) emotional stress and low productivity (Barnston, 1988). A 2009 study in Nairobi's informal settlements found that mortality rate due to pneumonia among children was higher during wet and beginning of cold season compared to the other seasons (Ye et. al., 2009). The external building envelope should protect inhabitants from temperature extremes and provide passive thermal control for comfortable, healthy indoors. This study proposes materials for walls to ensure healthy indoor thermal environment is maintained in residential houses in Nairobi.

Passive design is the use of features in buildings to work with natural processes rather than by artificial heating and ventilation (Beggs, 2007). Energy efficiency is an important feature in making a building material environmentally sustainable. The findings of the research will contribute to promotion of passive design through the development of criteria of selecting suitable materials for building.

1.7 Scope, Limitations and Assumptions

The thesis assessed the indoor thermal environment of living rooms only in single storey residential buildings in and around Nairobi, Kenya. It considered two thermo-physical properties: thermal mass and thermal transmittance of walls. The focus of this work is to analyze which of these two properties is desirable for walls in the sub-tropical highland climatic areas climate.

In this study, the evaluation of the indoor conditions of the case study buildings includes thermal information and energy consumption. Due to time and efficiency limitations the data on occupancy, metabolic activities and clothing are generalized for various periods of the day with the assumptions that they represent daily conditions over the whole year. Furthermore, because of time and cost restrictions this study could only be conducted on three buildings to represent conditions of such buildings in Nairobi.

The following other assumptions were made:

1. That the three case buildings are representative of typical single storey buildings in Nairobi in terms of building construction, occupancy, domestic equipment, metabolic activities and clothing of the inhabitants throughout the year.

2. That the adaptive comfort model in ASHRAE Standard 55 (2010) and the admittance method (CIBSE, 2006) of calculating operative temperature used in Ecotect 2011 thermal simulation software may be applied to determine thermal comfortable conditions in the study area.

3. That the typical thermal conductivity, density and specific heat capacities referred from ISO 10456 (2007)are equal to the actual properties of the building materials used in Nairobi. In reality the properties of the same building material varies with source.

4. That the climatic data for Dagoretti Weather Station which was used for thermal simulation is representative of the climatic conditions throughout Nairobi.

5. The use of measured air temperature measurements to assess thermal comfort assumes that air temperature equals operative temperature. ASHRAE Standard 55 (2010) allows this when there is no radiant and/or radiant panel heating or radiant panel cooling system, no major heat generating equipment in the space, where windows are shaded and no forced air movement, and when occupants are engaged in nearly sedentary activities.

CHAPTER TWO
LITERATURE REVIEW

2.1. Introduction

This chapter presents literature review on three related areas of study: sustainable building, the laws that govern heat transfer through building materials and the human perception of indoor thermal environment. The laws and methods of heat transfer predict the behaviour of materials subjected to heat energy depending on their thermo-physical properties. Exploring buildings' thermal behaviour is necessary to predict occupants' satisfaction and to examine means to achieve better indoor thermal environments and energy efficiency for sustainable building.

2.2. Sustainable Building

Sustainability may be defined as "meeting the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland Commission, 1987). It requires society to function and exist within boundaries of earths capacity and provides for intergenerational equity. Sustainable development consists of balancing local and global efforts to meet basic human needs without destroying or degrading the natural environment (Kates et al., 2005). There is growing concern that human activities are affecting global and local ecosystems severely enough to potentially cause permanent changes to some ecosystems, potentially causing them to crash (Steffen and Tyson, 2001).With the overall context of inter-generational equity, the risk to the environment, society and the economy must be minimized over both the short and the long term.

The principles of sustainability may be applied in buildings during design, creation, functioning and demolition, and the accompanying material use, energy consumption, and waste production (Yudelson, 2007). This is "sustainable building" defined as responsible use of processes that are environmentally sensitive and resource-efficient throughout a building's life-cycle: from siting to design, construction, operation, maintenance, renovation, and demolition (U.S. Environmental Protection Agency, 2016).

Buildings contribute significantly to the environmental burden. Worldwide, buildings consume massive amounts of energy. It is estimated that up to 40)% of all primary energy produced worldwide is used in buildings and that existing buildings are responsible for 24% of global CO_2 emissions (United Nations Environment Programme, 2007).

In addition, buildings are responsible for pollution, water consumption, land degradation, resource consumption, waste production and loss of biodiversity incurred throughout the life cycle of buildings, from raw material extraction, processing, construction, building operation and demolition. Sustainable building is an important aspect of the broader framework of sustainability, and can contribute to environmental(encompassing ecosystems and resources), social and economic benefits.

2.2.1 Environmental Benefits of Sustainable Building

The environmental benefits of sustainable building include: reductions in the consumption of building materials, water, and energy; and a reduced ecological footprint. Halliday (2008) identified a range of criteria to which buildings should be subject to improve sustainability:

i) enhance biodiversity and not using materials sourced from threatened species or taken from sensitive or threatened environments, and where possible improve natural ecosystems and habitats through appropriate planning and resource consumption;

ii) use resources effectively by not unnecessarily consuming resources during materials sourcing, construction, building function, and demolition, and by reducing energy, water and materials waste due to inefficiency, short product lifespan, poor construction and manufacturing processes;

iii) minimise pollution by reducing dependence on materials, products, energy, transport, and management practices that produce waste or other pollutants;

In building design, two specific solutions have been identified as having great potential to reducing energy consumption: use of local materials and passive design.

Significant energy is consumed during the extraction, processing and transportation of materials as well as during the construction. Morel et al. (2001) found that use of local materials during construction could reduce energy costs by more than a factor of three and could reduce impacts from transportation by more than a factor of six. The local materials studied included rammed earth, stone, timber and were compared to use of imported concrete which requires significant energy for processing.

Passive design is the implementation of features into buildings that work in collaboration with and utilize natural processes for heating, ventilation and lighting (Beggs, 2007). The purposes is to minimize energy consumption while providing comfortable living conditions. Yudelson (2007) identified four major design principles enable architects and builders to incorporate passive design into their buildings: solar orientation; maximization of solar gain through low-surface loss and high internal volume; high mass within the insulation and avoiding of shading.

2.2.2 Social Benefits of Sustainable Building

People’s desire to live in an environmentally sustainable manner and with a smaller ecological footprint has increased(Crocombe, 2007). For the individual or family, the primary place where lifestyle changes can be implemented is in the home. The regulation of internal temperatures to ensure comfortable living takes up a large proportion of household energy consumption(Martin and Verbeek, 2006). Therefore, the implementation of passive design principles into homes represents an appropriate method of reducing household environmental impact .

The social benefits of sustainable building are achieved by improved indoor environmental quality leading to better living conditions and health for building residents (Yudelson, 2007).Buildings with good overall environmental quality can reduce the rate of respiratory diseases, allergies, asthma and sick building syndrome, and enhance workers' performance.

Frontczak & Wargocki, 2011 identified four parameters for measuring indoor environmental quality are:

i) thermal comfort,
ii) visual comfort,
iii) acoustic comfort and
iv) good air quality

Thermal comfort is “that condition of mind which expresses satisfaction with the thermal environment”(ISO 7730, 2006). Thermal comfort standards define the thermal environment as a function of four physical variables (air temperature, mean radiant temperature, relative air velocity and air humidity) and two variables related to people (activity level and clothing).

Visual comfort is defined as “a subjective condition of visual well-being induced by the visual environment” (EN 12665, 2002). Visual conditions are characterized by such parameters as luminance distribution, illuminance and its uniformity, glare, colour of light, colour rendering, flicker rate and amount of daylight (EN 12464-1, 2002). Visual comfort may be achieved by incorporating natural light and views to ensure building users' comfort and enjoyment of their surroundings, reducing lighting energy needs in the process.

Navai and Veitch (2003) defined acoustic comfort as “a state of contentment with acoustic conditions”. Sound is characterized by the sound pressure level in a short-term and long-term period and by sound frequency. The acoustic environment is influenced by such physical room properties as sound insulation, absorption and reverberation time (Cowan, 1994). In the education, health and residential sectors, acoustics and proper sound insulation play important roles in helping concentration, recuperation, and peaceful enjoyment of property.

Acceptable air quality is defined as “air in which there are no known contaminants at harmful concentrations as determined by cognizant authorities and with which a substantial majority (80% or more) of the people exposed do not express dissatisfaction” (ASHRAE Standard 62.1., 2007). Acceptable air quality is achieved by bringing a breath of fresh air inside, delivering high indoor air quality through good ventilation and avoiding materials and chemicals that create harmful emissions.

Studies of the health benefits of sustainable building focus primarily on indoor environmental quality. Health effects result from environmental stimuli interacting with the body’s physical systems, especially respiratory, skin, neural, and visual pathways. Studies have shown a causal relationship between the building environment and illness symptoms in three areas: (i) sick building syndrome (ii) asthma and allergies, and (iii) communicable and respiratory diseases (Brightman &Moss, 2001, Fisk 2001).

Psychological effects such as comfort, satisfaction and well-being are generated through perceptual and sensory processes that interpret environmental information in terms of its effect on current needs, activities, and preferences. These effects have consequences for work performance and productivity, stress and wellbeing (Seppänen*et al.*, 2005). A number of studies indicate that certain building features such as daylight, views, connection to nature, and spaces for social interaction, appear to have positive psychological and social benefits (Leeman &Bordass 2001). The benefits include reduced stress, improved emotional functioning, increased communication, and an improved sense of belonging

2.2.3 Economic Impact of Sustainable Building

For the individual, the economic benefits of sustainable design stem largely from reductions in costs associated with resource consumption such as expenditure on energy, water and in some cases, building materials (Crocombe, 2007, Yudelson, 2007).

There are, however, broader economic benefits provided by sustainable design, such as the opening of new markets for the production of new technologies and materials, and the mitigation of potential costs associated with the emission of pollutants such as greenhouse gases. Studies show that the potential financial benefits of improving indoor environments exceed the costs by a factor of 8. (Fisk & Rosenfeld, 2000; Blengin i& Di Carlo, 2008).

Halliday (2008) suggests the following measures to benefit economically from sustainable building:

i. Optimize site and orientation. One obvious strategy to reduce first costs is to apply appropriate siting and building orientation techniques to capture solar radiation for lighting and heating. Fully exploiting natural heating and cooling techniques can lead to smaller heating, ventilation and air conditioning costs.
ii. Re-use/renovate older buildings and use recycled materials. Re-using buildings, as well as using recycled materials and furnishings, saves virgin materials and reduces the energy required to produce new materials. Re-using buildings may also reduce time (and therefore money) associated with site planning and permitting.
iii. Avoid structural overdesign and construction waste. Optimal value engineering and advanced framing techniques reduce material use without adversely affecting structural performance.

2.2.4 Challenges in Sustainable Building

Despite the many benefits of sustainable building, there remain challenges in acceptance and implementation of the practice. An OECD (2003) report identified three main challenges: i) the long lived nature of building products; iii) discrepancy between owners and users; and iii) the spatially fixed nature of buildings.

The first challenge is a difficulty of convincing builders and users to invest in sustainable practices in a project with a long life cycle. Improving the energy efficiency of buildings usually means extra capital costs, but these are often recovered by a reduction in energy cost during its life. Life-cycle cost assessments often indicate that the extra capital cost of making energy improvements can be more than recovered from energy savings during the long service lives of buildings (Kats, 2003). However, consumers generally reject the efficiency option if their investment is not paid for through energy savings within a short time (Blengini& Di Carlo, 2008).Where the benefits seem to be gained over a long period, users may consider as too distant gains and be unwilling to invest in sustainable options.

Secondly, building owners are often not the users. This owner/user discrepancy has caused “principal-agent” problems for improving the energy efficiency of rented buildings (OECD, 2003). It is usually tenants who pay energy bills and benefit from improved energy efficiency, but this is generally not reflected in the rent level. As a result, when landlords are taking decisions concerning the design of buildings, they have inadequate incentive to make an extra investment for energy efficiency.

Thirdly, the building sector is distinguished by the physical nature of its production process and its products with a large proportion of the work taking place at the site. The unique nature of the building sector has led to the low level of standardization in the design and production of buildings and the failure to exploit the economies of scale resulting from limited repetition (Finkel, 1997).Most buildings are designed and constructed in the “custom-made” manner – that is, individual buildings are designed to satisfy specific requirements of clients in light of the specific conditions of the site, such as its area and shape, flexibility of the ground, climate of the area, surrounding environment, including the situation of neighbouring buildings, and infrastructures.

2.3 Heat Transfer in Buildings

The nature of heat transfer between the external environment and building materials will affect indoor temperature conditions. Comfortable indoor temperatures are a necessary condition for sustainable building. To understand and control the thermal environment in buildings, it is important to consider the principles that contribute to it. This section presents the concepts of heat transfer in buildings and the influence of the thermo-physical properties of the materials used in construction of the building envelop. It covers the mechanisms of flow of energy, the thermo-physical properties of materials used in the building envelop and their effect on indoor temperatures.

2.3.1 Heat Transfer Mechanisms

Heat transfer is the movement of energy due to temperature difference and is largely governed by the First and Second Laws of Thermodynamics: that the increase in internal energy of a closed system is equal to the difference of the heat supplied to the system and the work done by it and that heat will flow from a hotter location to a colder location(Lienhard,2008, p.7).The fundamental modes of heat transfer are radiation, conduction and convection.

All matter with a temperature above absolute zero emits thermal radiation in the form of electromagnetic waves. Thermal radiation propagates without the presence of matter through vacuum. It is a direct result of the random movements of atoms and molecules in matter(Kondepudi,2008). Since these atoms and molecules are composed of charged particles (protons and electrons), their movement results in the emission of electromagnetic radiation, which carries energy away from the surface.

The Stefan-Boltzmann law states that the total energy radiated is directly proportional to the fourth power of the body’s temperature (Çengel, 2003):

$$Q = \varepsilon\sigma T^4 \qquad \text{(eq.2.1)}$$

Where

Q is the heat transfer in W/m^2,

$\varepsilon$is the emissivity (1.0 for ablack body),

$\sigma$is the Stefan-Boltzmann constant(5.670373×10^{-8} W m^{-2} K^{-4}**)**

T is the absolute temperature in Kelvin.

Given the low value of the Stefan-Boltzmann constant, radiation is only significant for very hot objects such as the sun and, in buildings, radiant heating equipment.

The primary source of energy on earth is the sun’s radiated energy which arrives in the form of heat and light travelling as shortwave radiation. When this energy hits a surface, it is reflected, transmitted or absorbed (Atheinitis&Santamouris, 2002). The portion of the radiant heat that is absorbed is transformed to heat energy which is then transferred by conduction within a solid or between solid objects in thermal contact.

Heat conduction occurs as hot, rapidly moving or vibrating atoms and molecules interact with neighbouring atoms and molecules, transferring some of their energy to these neighbouring particles (Kaviany, 2008). Fourier's Law of Heat Conduction (Equation 2.2) states that the rate of heat transfer through a material is proportional to the negative gradient in the temperature and to the area, at right angles to that gradient, through which the heat flows (Venkanna, 2010).

$$\vec{q} = -k\nabla T \qquad \text{(eq. 2.2)}$$

Where

$\vec{q}$ is the local heat flux density, W/m^2

k is the material's conductivity, W/mK

∇T is the temperature gradient, K/m.

Convection is the transfer of heat from one place to another by the movement in liquids and gases. To transfer heat from a solid to a fluid, the fluid moves across a radiant surface to agitate the molecules which when heated move away and are then replaced by new unheated molecules (Burmeister, 1993).Newton's Law of Cooling(equation 2.3) states that the rate of heat loss of a body by convection is proportional to the difference in temperatures between the body and its surroundings.

$$Q = hA(T_{body}-T_{env}) \qquad \text{(eq. 2.3)}$$

Where

Q is the heat transfer (W/m^2)

h=heat transfer coefficient of the surface (W/m^{2}K)

A = the heat transfer surface area (m^2)

T_{body} =temperature of the surface of a body (K)

$T_{env =}$ temperature of the environment (K)

Convection may therefore be naturally caused by buoyancy forces that result from density variations due to temperature differences in the fluid or forced convection induced by external means such as fans.

2.3.2 Thermo-physical Properties of Materials

Thermo-physical properties of material are those properties affecting the transfer and storage of heat that vary with temperature, pressure and composition, without altering the material's chemical identity (Venkanna, 2010).The properties of materials that determine radiant heat transfer are absorptivity (α), reflectivity(r),emissivity(ε) and transmissivity(ĩ). The ability to absorb, reflect or emit absorbed energy depends on the colour, texture and clarity of the surface material. Transmissivity is a property associated with transparent objects (Çengel, 2003).For most of the materials commonly used in construction(other than glass and metals)and within the normal temperatures range, emissivity is equal to absorptivity.

The properties that determine heat transfer by conduction in solids are density, specific heat capacity, and thermal conductivity. Density is the mass of a material per unit volume in Kg/m^3 and specific heat capacity (J/KgK) is the amount of heat per unit mass required to raise the temperature by one degree. The product of solid materials density and specific heat capacity is the volumetric heat capacity (VHC) in J/m^{3}K.VHC is the ability of a given volume of substance to store internal energy. Thermal conductivity (W/mK) is rate of heat transfer per unit thickness of a material from face to face per unit temperature difference between two faces in (Venkanna, 2010).

Materials that are used in building envelopes will have a wide range of these primary properties and therefore differences in absorption, storage and transfer of heat energy. The mapping in Figure 2.1 compares six materials used in construction of walls. While timber and expanded polystyrene have low thermal conductivity and capacity, concrete and stone have high thermal capacity and conductivity.

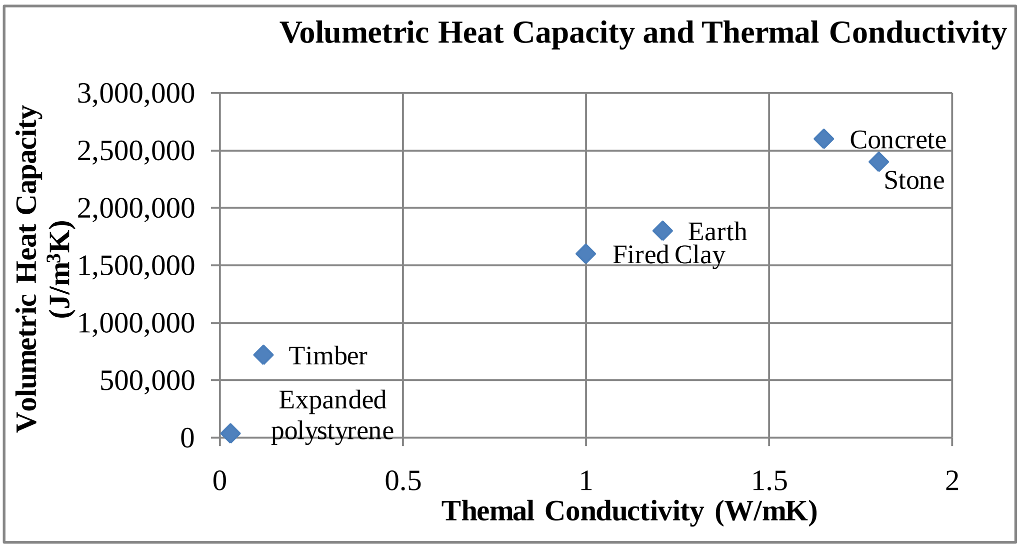


Figure 2.1 Mapping of Building Materials' Thermal Properties.

Source: ISO 10456 (2007)

In building elements, thermal transmittance is the measure of the rate of transfer of heat through one square metre of a structure in W/m²K. Thermal transmittance takes into account heat transfer due to thermal conduction, thermal radiation and thermal convection (ISO 6946, 2007). For a building element like the wall, the thermal transmittance is calculated as follows:

$$U = \frac{1}{(R_{so} + R_{si} + R_1 + R_2 + ..)} \qquad \text{(eq. 2.4)}$$

Where

U is the thermal transmittance in W/m^{2}K

R_{so} is the fixed external resistance;

R_{si} is the fixed internal resistance and

R_1+R_2 … is the sum of all the resistances of the building materials in the constructional element.

Thermal resistance in m^2K/W is calculated as the thickness of the material divided by its thermal conductivity R_{so} and R_{si} values due to radiation, conduction and convection heat transfer between the material surface and the air are given in ISO 6946 (2007).

For a 200mm thick wall plastered on the inside, the thermal transmittance is calculated as follows:

$$U = \frac{1}{\left(R_{so} + \ R_{si} + R_{st} + R_{pl}\right)}$$

Where R_{so}(Outside surface resistance) = 0.04 (ISO 6946 (2007)

R_{so}(Insidermne surface resistance) = 0.13 (ISO 6946 (2007)

R_{st} (thermal resistance of stone) is given by $1/k_{st}$ x d_{st}

R_{pl} (thermal resistance of plaster) is given by $1/k_{pl}$ x d_{pl}

Where

k_{st}(thermal conductivity of stone) = 1.8W/mK (ISO 10456 ,2007)

d_{st}(thickness of stone)= 0.2m

k_{pl}(thermal conductivity of stone) = 1.0W/mK (ISO 10456 ,2007)

d_{pl}(thickness of stone)= 0.013m

U= 1/ (0.04 + 0.13+ (1.8*0.2) +(1.0 * 0.013)

=3.4W/m^2K

Thermal mass are materials that have capacity to absorb, store and release heat measured as the heat capacity per square metre of a material in J/m^2K. The higher the thermal mass, the more heat the element is able to store. It takes into account specific heat capacity, density and thickness of the material layers forming the element (Venkanna, 2010). For a building element like the wall, the thermal mass is calculated as follows:

$$K = \sum(ci.\rho i.di) \qquad \text{(eq. 2.5)}$$

Where:

K is the thermal mass (J/m^2K)

ci is specific heat capacity of material layers (J/kgK),

ρi is density of material layers (kg/m^3) and

di is the thickness of material layers (m)

For a 200mm thick wall plastered on the inside, the thermal mass is calculated as follows:

$K = (c_{st*}\, p_{st*} d_{st}) + (c_{pl*}\, p_{pl*} d_{pl})$

Where

c_{st}(specific heat capacity of stone) = 1000J/Kg/K

p_{st}(density of stone) = 2400Kg/m^3

d_{st} (thickness of stone) = 0.2m

c_{pl}(specific heat capacity of plaster) = 1000J/Kg/K

p_{pl}(density of plaster) = 1800Kg/m^3

d_{pl} (thickness of plaster) = 0.013m

K=(1000*2400*0.2) + (1000*1800*0.013)

=503,400J/m^2K

As far as the thermo-physical properties of building materials are concerned, two types of wall constructions are identified: thermal insulators with low thermal transmittance and thermal mass with high heat capacity.

2.3.3 Effect of Walls on Indoor Temperature in Buildings

The mechanism of heat transfer in buildings begins during the day, when the external wall temperature increases as a result of the incident solar radiation. As the time passes, some of the heat is absorbed by the wall and the temperature increases according to the material's thermal capacity. The heat moves through the wall, towards the inside surface. During the night, a reverse process takes place, as the temperature outside decreases and there is no solar radiation (Dwyer, 2012).As the outdoor air temperature and solar radiation intensity change significantly during day and night, the indoor air temperature also varies with time(Figure 2.2).

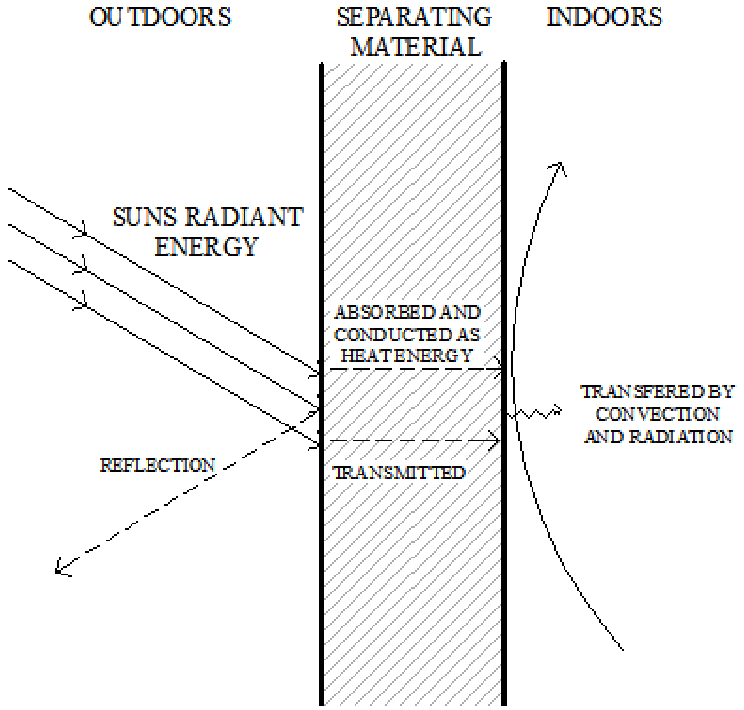


Figure 2.2 Mechanisms of heat transfer of the sun's energy on a wall

The periodic sinusoidal relationship between these external and indoor variations is expressed as the decrement factor and the time lag of the building element. Time lag is the time difference between the temperatures maximum at the outside and inside when subjected to periodic conditions of heat flow (Figure 2.3). The decrement factor is the ratio of the maximum outside and inside surface temperature. The time lag and decrement factors are dependent on material's density, thermal capacity, thermal conductivity, surface resistance and the time cycle of the temperature variation. (CIBSE Guide A3, 2006).

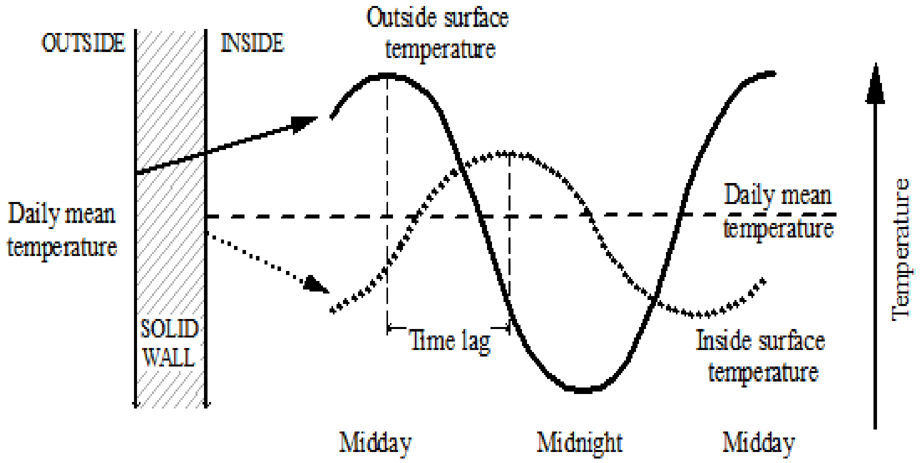


Figure 2.3 Daily temperature profiles at outside and inside surfaces of a wall.

Source: Dwyer (2012)

In climatic regions with high diurnal range, materials of high thermal mass have been found to be more effective than insulators in minimizing temperature fluctuations. Earth blocks and rammed earth walls were found to be most effective in hot dry Sanaa, Yemen, (Alhaddad& Jun, 2013) and San Pedro de Atacama, Chile (Palme, Guerra& Alfaro, 2014). In warm dry-summer continental climate in Yozgat, Turkey, it was found that walls with high thermal mass such as stone and soil blocks have a better moderating effect on temperature swings compared to low thermal capacity and high insulation materials such as the structural insulated panels and timber frame(Elias-Ozkan, et al., 2006).

In other climatic areas studies have produced different results. In cool tropical Nairobi, Kenya, Ogoli (2003) constructed test chambers to study effect of materials on indoor temperatures in enclosures. The study concluded that high thermal capacity stone wall with concrete roof tiles were more effective in moderating extreme temperatures compared to those with low thermal capacity timber wall with galvanized iron sheet roof.A similar test chamber study by Heathcote& Moor (2007) in humid subtropical climate of Sydney, Australia found insignificant difference in performance of mud bricks, insulated panels and fired clay bricks. On the other hand, Kemanjou & Mb (2012) concluded that lightweight insulating wood provided better thermal comfort than high thermal mass concrete bricks in hot and humid tropical climate. This study was in Duala, Cameroon.

2.4 Thermal Comfort in Buildings

This section presents the concept of human perception of indoor thermal environment and the standards developed to achieve thermal comfort. It has been shown that in certain seasons, man’s physical strength and mental activities are at their best within a given range of climatic conditions, and outside this range efficiency lessens, while stresses and the possibility of diseases increase.

2.4.1 Heat Balance and Adaptive Models

Thermal comfort is defined as "that condition of mind which expresses satisfaction with the thermal environment" (ISO 7730, 2006). The parameters that determine thermal comfort. The acceptability of the indoor thermal environment in buildings can be predicted using two methods: the heat balance modeling and adaptive modeling.

The Heat Balance approach is based on analysis of the thermal comfort undertaken by Fanger in the 1970s.Fangerused physiological data obtained by climate chamber studies involving subjects exposed to controlled environmental conditions (de Dear and Brager, 2001, Fanger, 1972). Heat balance approach is based on the assumption that a necessary condition for thermal comfort is a balance between the metabolic heat production and the heat loss from the body. In order to stay healthy, the internal body temperature must be kept at 37˚C and heat produced must be balanced by the heat lost from the body (Humphreys, 1995).

The approach developed a comfort equation (2.6) that takes into account six factors:

i. Air temperature or dry-bulb temperature is the average temperature of the air surrounding the occupant and affects the rate of convective and evaporative body heat loss.

ii. Mean radiant temperature is the amount of radiant heat transferred from a surface, and it depends on the material's ability to absorb or emit heat. It affects the rate of radiant heat loss from the body.

iii. Air velocity is the rate of air movement at a point and affects body heat transfer by convection and evaporation. The faster the motion, the greater the rate of heat flow by both convection and evaporation.

iv. Relative humidity is the ratio of the amount of water vapour in the air to the amount of water vapour that the air could hold at the specific temperature and pressure. It affects the rate of evaporation from a person's skin. At high relative humidity evaporation, and therefore heat loss, is decreased

v. Metabolic rate is the level of transformation of chemical energy into heat and mechanical work by metabolic activities within an organism. Metabolism results in heat production

vi. Clothing insulation is the amount of thermal insulation worn by a person influences the heat loss and consequently the thermal balance. Layers of insulating clothing prevent heat loss and can either help keep a person warm or lead to overheating. (ASHRAE Standard 55, 2010)

The heat balance equation is expressed by Fanger(1972)as:

$$M = W + C + R + E_{sk} + C_{res} + E_{res} \qquad (W/m^2) \qquad \text{(eq. 2.6)}$$

Where:

M = metabolic heat production;

W = external work;

C = heat loss by convection;

R = heat loss by radiation;

E_{sk} = evaporative heat loss from skin;

C_{res} = convective heat loss from respiration;

E_{res} = evaporative heat loss from respiration;.

The Adaptive Comfort models add human behaviour to climate variables. De Dear and Brager (2001)found that the thermal expectations of building occupants, and their subsequent expectations for indoor comfort, will depend on outdoor temperature. The adaptive principle suggests that people will adapt to certain climatic conditions and that comfort temperature is a result of the interaction between the subjects and thermal environment. Building occupants are not simply passive but rather, play an active role in determining their own thermal preferences. Nicol and Humphreys (2001) also concluded that people with more opportunities to adapt themselves to the environment will be less likely to suffer discomfort. Since adaptive formulas are based mainly on human behaviour and outside weather conditions, they are usually a result of extensive surveys of thermal comfort in a wide range of buildings, climates, and cultures.

The Heat Balance approach assumed that the biophysical relationship between the external environment and the human body are universally applicable across all buildings, climatic zones and populations (Parsons 1994). This claim has been questioned by researchers since the 1990s arguing that it ignores cultural, climatic and social differences and denying possibility of adaptation (Brager & de Dear, 2001). The adaptive approach is also simpler to apply in practice. Whereas the heat balance model requires the collection of a comprehensive range of data, including an estimation of clothing, insulation and metabolic heat production the adaptive formula is essentially a regression equation that relates the desired temperature indoors to the monthly average temperature outdoors(Humphreys, 1995).

Following the work of de Dear and Brager (2002)in a study of 160 buildings in North America, Europe, Asia and Australia and covering a broad spectrum of climate zones, an adaptive standard was developed that is used for the ASHRAE Standard 55 (2010). It defines zones within which 80% or 90% of building users might expect to find the conditions acceptable (Figure 2.4). The comfort zone is determined by the adaptive formula:

$$T_C = 17.8 + 0.31T_0 \quad \text{...(eq. 2.7)}$$

for80% acceptability T_C is±3.5°C (That is zones within which 80%of building users might expect to find the conditions acceptable); and for 90% acceptabilityT_C is±2.5°C .

Where

T_c is the comfortable indoor temperature;

T_o is the monthly mean outdoor temperature.

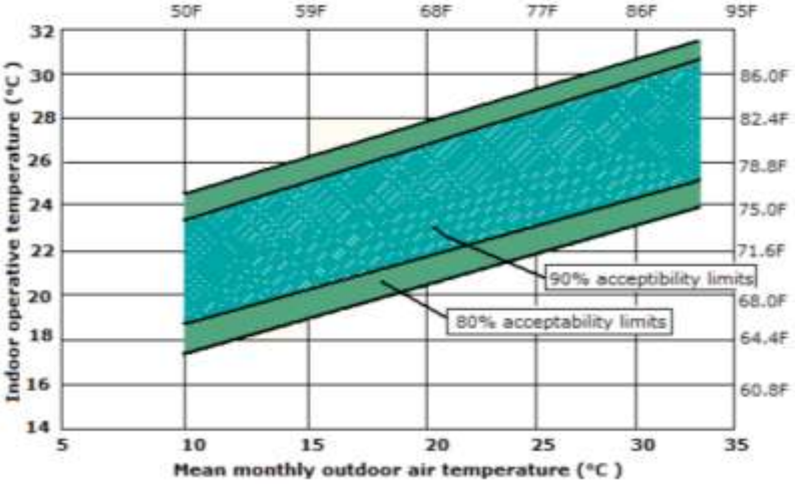


Figure 2.4 Acceptable temperature ranges for naturally conditioned buildings.

Source: ASHRAE Standard 55 (2010)

The comfortable indoor temperature Tc is a resultant or effective temperature that incorporates air temperature, mean radiant temperature and air velocity. The thermal effect of humidity on the comfort of sedentary persons is small and comfort is maintained over a wide range of relative humidity between 40% and 70% (Wolkoff & Kjaergaard, 2007).

According to ISO 7726 (2012) this resultant temperature is the operative temperature (t_o) which is calculated as:

$$t_o = \frac{(t_{mr} + (t_a \times \sqrt{10v}))}{1 + \sqrt{10v}} \qquad (2.8)$$

Where

t_o = operative temperature,
t_a = air temperature,
t_{mr} = mean radiant temperature,
v = air speed (m/s) (ISO 7726, 2012)

2.4.2 Long Term Control of Thermal Discomfort

As the thermal environments in buildings will vary throughout the year, various methods of controlling long term thermal comfort have been developed. One method is by developing indices for evaluating suitability of buildings in the long term. Such methods often calculate the percentage of hours when uncomfortable conditions are recorded, or cumulate the number of degrees outside a given thermal comfort temperature range (Carlucci & Pagliano, 2012). Long term thermal discomfort may also be controlled by regulating the properties of the construction materials in building envelopes.

The two main indices for long term thermal discomfort are proposed by ISO 7730 (2006) and ASHRAE (2010). These are degree-hours criterion (DhC) and the percentage of likely discomfort hours (percentage outside range: POR). They are based on comfort models and measure to what extent the temperatures have been outside the comfort range.

In the DhC time during which actual operative temperature exceed the specified comfort range during occupied hours is weighted by the number of degrees the range has been exceeded. The POR requires calculating the percentage of hours of occupation when the operative temperatures are outside a specified comfort range. It is a straightforward and simple method to compare the comfort performance of different buildings. It is also possible to specify the maximum allowable percentage. The European Standard EN 15251 allows up to 5% discomfort(CEN, 2007).

However, POR does not give information about the severity of the uncomfortable hours which may be more important than frequency. Though DhC has no theoretical upper limit, the weighting of degree takes into consideration the severity of discomfort as well as the hours of discomfort (Carlucci & Pagliano,2015).

The relationship between indoor thermal environment and properties of building materials forms a basis for long term control of thermal discomfort. Building regulations in individual countries specify the required thermal properties of the building elements that take into account thermal comfort requirements and climatic conditions. Most of the regulations use the thermal transmittance values as a basis. In the United Kingdom the Building Regulations (2010) specifies maximum thermal transmittance values (U-values) of 0.25 W/m^{2}K. In Japan, the Design and Construction Guidelines on the Rationalisation of Energy Use for Homes are set for residential buildings for six different climatic regions ranging from 0.35 W/m^{2}K to 0.53W/m^{2}K for walls (IEA, 2008).

In the United States, the International Energy Conservation Code 2004 (IECC 2004) sets rules for residential (with less than 4 floors) and for small and simple commercial buildings for eight climatic zones (International Energy Agency, 2008). IECC (2004) distinguishes between light weight walls from massive walls in setting U-values. These values range from 0.32 to 0.47 W/m^{2}K for wood frame walls and 0.32 to 1.12W/m^{2}K for massive walls.

The South African National Standard for Energy Efficiency in Buildings (Sans 204, 2011, 4.3.3) uses both the U-value and a CR-value. CR-values is an arithmetic product of the thermal capacity and thermal resistance value in hours. Thermal resistance is the reciprocal of thermal transmittance. For residential house, the standard sets the minimum CR-value between 80-100 hours depending on the climatic zone. The higher the CR-value the greater is the ability of the wall to moderate and minimize effect of external climate conditions in building interiors.

Summary

Chapter Two presented the review of existing literature on the subject of this research: sustainable building, heat transfer through building materials and human indoor thermal comfort. The issues are summarized below:

1. Buildings contribute significantly to the environmental burden contributing to resource consumption including up to 40 % of all primary energy produced worldwide.
2. Sustainable building practices such as passive design have environmental, social and economic benefits to the building residents at the local level as well as contributing to the global efforts of sustainable development
3. Challenges of sustainable building include the long period of time it takes to recover costs of implementing sustainable solutions, discrepancy between interests of owners and users and the difficulty of standardizing building solutions due to different site conditions and user requirements.
4. The parameters to measure indoor environmental quality are thermal comfort, visual comfort, acoustic comfort and air quality
5. Of the three main modes of heat transfer (radiation, conduction and convection), conduction is the most significant in buildings that are naturally ventilated where there is no direct solar radiation, convective cooling or radiant heating
6. There are two main thermo-physical properties of building elements that affect indoor temperature: thermal transmittance which takes into account all three modes of heat transfer and thermal mass that depends on heat capacity and density of the materials.
7. That the relative importance of thermal transmittance and thermal mass has been found to vary depending on the climatic conditions. Thermal mass has been found to be more significant in areas with high diurnal temperature variations.
8. The perception of thermal comfort depends on the adaptation and expectations of building occupants in specific climatic conditions. The temperature at which people feel comfortable is linearly related to the prevailing external temperatures.
9. The index that measures the severity of thermal discomfort is the Degree Hours of Discomfort (DhC). This is the time in hours during which actual operative temperature exceeds the specified comfort range weighted by the number of degrees the range has been exceeded.

CHAPTER THREE
METHODOLOGY

3.1 Introduction

This is a causal-comparative quantitative research to study the cause-effect relationships between indoor temperature, outdoor temperature, and thermo-physical properties of building materials in the subtropical highland climate of Nairobi, Kenya. Primary data was collected through a case study method in existing buildings and then a simulation process used to predict the level of thermal discomfort when materials with different thermo-physical properties are used.

3.2 Research Approach

Previous studies of similar nature have used two different strategies to collect primary data. Ogoli(2003) and Heathcote & Moor (2007) constructed similar test chambers with different construction materials to collect the internal and external temperature data. On the other hand, Elias-Ozkan et al., (2006), Kemanjou and Mb (2012) and Alhaddad and Jun (2013) measured existing buildings and used observation to collect data to model and use computer simulation to predict behaviour of other materials. The first strategy allows use of only actual measured data in regulated environmental conditions. However, it is expensive and time consuming to build such test buildings. This research applied the second strategy which incorporates effects of actual domestic circumstances on thermal conditions such as human occupants as well as spatial information in naturally conditioned circumstances. The measured data is used to model, calibrate and verify information from simulation software.

Simulation is the process of developing a simplified model of a complex system and using the model to analyse and predict the behaviour of the original system. The reasons of using it is that real-life systems are often difficult or impossible to analyse in all their complexity, and it is usually unnecessary to do so anyway(Daneshjo, 2011). Simulation approach involves the construction of an artificial environment within which relevant information and data can be generated. This permit an observation of the dynamic behaviour of a system under controlled conditions.

3.3 Research Activities

The research was carried out in Nairobi, Kenya. Nairobi has a subtropical highland climate with a mean maximum temperature of24.9°C and mean minimum temperature of 13.3°C (Appendix 1).

The following research activities were carried out:

i. Measurement of indoor temperature, indoor relative humidity and outdoor temperature in three case study buildings.
ii. Collection of building information and occupants details in the three cases.
iii. Calculation of the thermal mass and thermal transmittance values of walls used in residential houses in Nairobi.
iv. Modeling and simulation for thermal discomfort

Measured air temperature data was used to enable comparison of the effects of natural stone walling, timber frame walling and insulated walling panels on indoor air temperatures in residential buildings in Nairobi. The data was also used to compare and verify temperature information from the computer simulation.

Indoor relative humidity, building information, occupants details, thermal mass and thermal transmittance values of walls were input data for the computer simulation.

3.3.1 Measurement of temperature and relative humidity

The first part of the research activities was to identify three typical single storey residential houses in different parts of Nairobi with different materials for case study. Three cases were selected for this research. Previous studies have used one (Alhaddad & Jun, 2013), two (Kemanjou & Mb, 2012) or three buildings (Elias-Ozkan et al.,2006). In this research, three cases were selected to be able to compare actual temperature measurements in buildings with three materials with significantly different thermo-physical properties. Verbal consent was given before studies were undertaken in the homes.

The houses are selected using purposive sampling where subjects are selected because of some predetermined typical characteristics. The following criteria were used in selecting study buildings:

i. Buildings within or around Nairobi
ii. Buildings constructed with different walling materials
iii. Buildings constructed with the same materials for the groundfloors, roofs, windows and doors
iv. Buildings with windows facing away from direct solar radiation
v. Single storey detached dwellinghouses
vi. Buildings whose owners would allow access for study

The three selected buildings were located at Thogoto which is about 20 km North West of Nairobi CBD (Thogoto House), Syokimau (Syokimau House)which is 22 km South East of Nairobi CBD and Dandora (Dandora House) which is about 15 km North East of Nairobi CBD (Figure 3.1). The walling materials considered were natural stone (high thermal mass, low thermal transmittance), timber (low thermal mass, low thermal transmittance) and concrete panels insulated with expanded polystyrene-EPS (high thermal mass and low thermal transmittance)

The Thogoto House was located near the junction of Thogoto-Ndeiya road and Kikuyu road in Kiambu County. The single storey house included a living room, kitchen, bath room and three bedrooms all covering 56 square metres. It had a concrete floor, timber frame walls and corrugated galvanized iron roofing sheets with a gypsum board ceiling. The house was home to seven residents: four adults and three school going children.

Syokimau House was located 22 kilometres south-east of Nairobi City Centre inside Nairobi County but near the boundary with Machakos County. The single storey house consists of a living room, kitchen, bath room and two bedrooms all covering about 36 square metres. Its construction is of concrete floor, walls of expanded polystyrene panels and pre-painted corrugated galvanized roofing sheets with a soft board ceiling. The house was home to four residents: three adults and one child.

Figure 3.1 Location Map of Case Study Houses

Source: Google Maps (2016)

Dandora House was located in Dandora Phase 1 estate about 15 kilometres north–east of Nairobi City Centre. The single storey house consists of a living room, kitchen, bath room and two bedrooms all covering about 40 square metres. Its construction included a concrete floor, natural stone walling and corrugated galvanized roofing sheets with a softboard ceiling. The house was home to two adult residents. Figure 3.2 shows the details of the three houses.

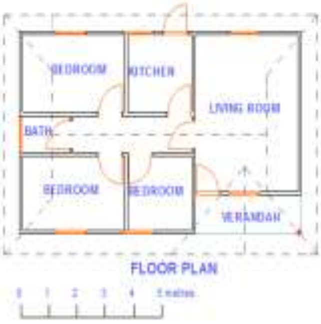
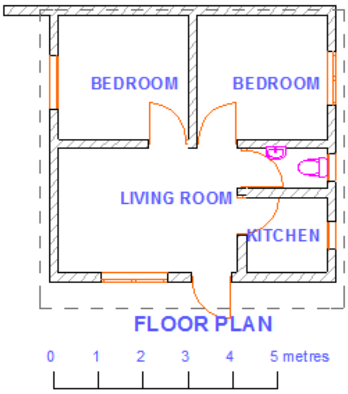
Study house	**Building image**	**Floor Plan**
1. Thogoto House		
2. Syokimau House		
3. Dandora House		

Figure 3.2 Details of three case study houses

Measurements of external air temperature, internal air temperatures and relative humidity were taken over thirty one days in the month of May 2015 at one hour intervals using data loggers. The month of May has a mean monthly temperature of 17.7°C which was about equal to the mean annual temperature of 17.6°C in Nairobi. May falls between the hot December to April period and the cold June to October months and was therefore representative of Nairobi's temperature conditions.

The instruments used were battery operated HOBO U12 Data logger (Figure 3.3) which measure internal temperature, relative humidity and external temperature. The data logger conforms to the requirements of ISO 7726 (2012) on accuracy and range.

Figure 3.3 HOBO U12 Temperature/ Humidity/External Data Logger -U12-012

Specifications of the data loggers were:

Manufacturer	Onset Computer Corporation.
Temperature Range	-20°C to +70°C
Humidity Range	5% to 95%
Temperature Accuracy	±0.35°C
Humidity Accuracy	2.5%
Dimensions:	58 x 74 x 22 mm

The data loggers were placed inside the buildings away from the windows, ceiling and wall surfaces and the external probe extended outside shaded from direct sunlight (Appendix 2). Indoor air temperature, indoor relative humidity and outdoor air temperature were recorded concurrently by the logger. The relationship between indoor and outdoor temperature was used to compare the behaviour of the different wall materials in the three houses. The indoor humidity measurement was used as input data for thermal simulation.

3.3.2 Collection of building information and occupants details

Onsite details of building construction and spatial measurements were collected using linen measuring tapes. The data was to be used for the purpose of modelling the buildings for computer thermal simulation. The spatial measurements are shown in Figure 3.2.

Data on metabolic activity, clothing insulation and domestic heat producing fittings and equipment was collected through observation. The corresponding values of metabolic heat (in W/m^2)and clothing insulation (m^2K/W) were referred from ISO 7730 (2006)(Appendix 9). The values of heat produced by domestic lighting fittings and equipment such as television were referred from Kreider, Curtiss and Rabl (2010)

The data on the number of occupants in each of the three houses on a typical weekday and weekend was collected through informal interview with the occupants. The data collection sheets are shown in Appendix6, 7 and8. This data together with Nairobi's climatic data and actual measurements of relative humidity was used to model the houses for thermal simulation.

3.3.3 Calculation of the thermo-physical properties of walls

The third activity of the study involved calculation of the thermal transmittance and thermal mass values of the external walls used in Nairobi. Five materials that are most commonly used were selected: natural stone: (47.4%), galvanized iron sheets (26.9%) bricks/blocks: (14.0%), mud (9.1%) and wood (1.9%) (Kenya Open Data, 2014). In addition structural insulated prefabricated panels with expanded polystyrene currently promoted for energy saving and faster construction by government owned National Housing Corporation (EPS Factory, 2014) were considered.

The wall assembly methods that were considered for the selected materials were:

i. Natural Stone: 200mm thick masonry construction:
    1. Without external render
    2. With external render

ii. Galvanised corrugated iron sheets(GCI): 30 gauge on cypress timber frame construction:
    1. Without internal lining
    2. With internal lining

iii. Brick and blocks: 200mm thick masonry construction plastered and rendered:
    1. Concrete
    2. Fired Clay

iv. Earth/ mud: monolithic construction:
    1. 300mm thick stabilized rammed earth (SRE)
    2. 400mm thick stabilized rammed earth

v. Timber: 20mm thick cypress boards on cypress timber frame construction:

    1. Without internal lining
    2. With internal lining

vi. Expanded polystyrene(EPS): prefabricated panels with cement sand facing:

    1. Single panel
    2. Double panel

Thermal transmittance values were calculated by the Ecotect2011 software using thermal conductivity values from ISO 10456(2007, Table 3). Thermal mass values of the multilayered walls were calculated using the Equation 2.5.

Specific heat capacity and density values were taken from ISO 10456(2007, Table 3).

3.3.4 Modeling and simulation for thermal discomfort

The third part of the study comprised computer modeling.The software used was Autodesk Ecotect 2011which is a whole building simulation software and uses three-dimensional (3D) models of the buildings. Geometric data is introduced to the software either from Computer Aided Design (CAD) programs or directly using its 3D-based interfaces (Marsh 2006).Ecotect software has been used by other researchers in similar studies (Alhaddad & Jun, 2013; Elias-Ozkan et al., 2006; Palme, Guerra & Alfaro, 2014)

Ecotect simulation tool uses the admittance procedure to calculate operative temperature and the adaptive thermal comfort formula to calculate monthly loads of discomfort. The admittance procedure is a technique for estimating energy transfers through the building envelope using thermal admittance, decremental factor and thermal time lag. It was developed by Chartered Institute of British Services Engineers (CIBSE, 2006, Guide A) to give a prediction method for dynamic thermal performance of buildings.

The admittance method takes into account both air and radiant temperature, the modifying effect on temperature fluctuations of the materials, solar heat gain, internal gains and external temperature. It is recommended by ISO Standard 13786:2007 (2007) for the characterization of the thermal behaviour of the building envelope.

Input data for the model was on-site spatial measurements of the three case study houses and details of building materials and assembly of walls, roofs, floors, windows and doors. Other data required was the building occupancy throughout a typical week, insulation due to clothing and heat gain due metabolic activities, light fittings and domestic equipment.

The three case study houses were modeled in Autodesk Ecotect 2011 software then thermal properties of the external walls varied in order to measure the effect of these changes on the thermal comfort of the occupants under different walls. The software calculates the indoor temperature conditions in each of the three building models for each of the twelve walls identified. Based on the comfortable temperature range from the adaptive thermal comfort formula, the degree hours of discomfort is determined by summing the products of the number of degrees that operative temperatures fall outside the comfort zone in degrees Celsius by the number of hours of discomfort.

$$DhC = \sum_{i=1}^{Oh}(wfi.hi) \in (0, +\infty) \qquad \text{(eq. 3.1)}$$

Where:

DhC is the annual degree hours of discomfort (^{o}C.hr)

wf is a weighting factor of degrees outside comfort (^{o}C)

h is time in steps of one hour (hr)

The comfort zone is determined by the adaptive formula

$$T_C = 17.8 + 0.31T_0 \text{for } T_C \pm 3.5^{o}\text{C} \qquad \text{(Equation 2.10)}$$

To determine the thermo-physical properties of materials for thermal comfort, a multi-variance regression analysis using Microsoft Excel data analysis tool was used to relate the annual degree hours of discomfort (DhC) with the walls thermal transmittance value and thermal mass value in the form:

$$y = Mx_1 - Nx_2 + C \qquad \text{(eq. 3.2)}$$

Where

y is the DhC

M is the coefficient of X Variable 1

x_1 is the X Variable 1 which is the wall's thermal transmittance

Nis the coefficient of X Variable 2

x_2 is the X Variable 2 which is the wall's thermal mass value

C is the intercept at the y-axis (DhC)

The maximum thermal transmittance value and/or the minimum thermal mass value required for thermal comfort are the values when DhC = 0

CHAPTER FOUR
RESEARCH FINDINGS AND DISCUSSIONS

4.1 Introduction

This chapter presents the findings of the research activities described in Chapter III and their interpretation. The findings are from the actual temperature measurements in three case study houses, and the results of the indoor thermal discomfort levels from Ecotect simulation software. The aim is to determine which properties will achieve least discomfort. Interpretation of the findings follows the presentation in form of discussions.

4.2 Findings

4.2.1 Case Study temperature measurements

The temperature measurements of three case study houses in Nairobi in the month of May show that the mean outdoor temperature in Thogoto, Dandora and Syokimau was 17.9^{o}C, 18.1^{o}C and 18.2^{o}C, respectively. These measurements were slightly higher than the climatic temperature figures for Nairobi's Dagoretti weather station which is 17.7^{o}C. The findings are in Appendix 3, 4 and 5and summarised in Table 4.1.

Table 4.1 Mean daily temperature measurements in three case houses in May

		THOGOTO	**SYOKIMAU**	**DANDORA**
	Mean Daily Temperatures(^{o}C)	Timber Frame	EPS Panel	Masonry stone
1	Mean indoor temperature	21.2	22.0	20.6
2	Mean outdoor temperature	17.9	18.2	18.1
3	Indoor, outdoor difference	3.3	3.8	2.5
4	Maximum indoor temperature	26.3	27.2	27.6
5.	Minimum indoor temperature	17.8	18.6	15.9

Mean indoor temperatures were higher (22.0°C)in the house made of expanded polystyrene (EPS) panels compared with that of timber (21.2°C) and stone (20.6 °C). In all three cases the indoor temperature was higher than the outdoor temperature. The observed mean indoor temperature of the living room was 3.8^{o}C, 3.3^{o}C and 2.5^{o}C above the mean outdoor temperature for the EPS, timber and stone wall buildings, respectively.

Figure 4.1 shows graphs of the mean daily indoor air temperature measured over 31daysin the month of May for the three houses. The living room of the EPS house was found to be warmer compared to the timber and stone houses.

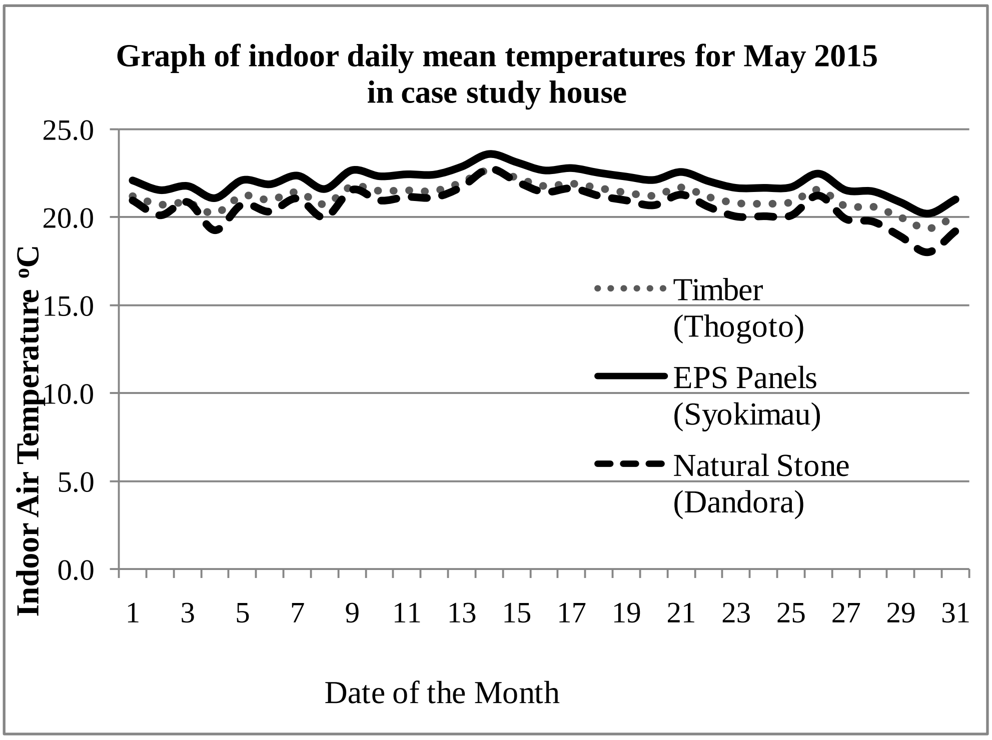


Figure 4.1 Mean daily indoor temperatures over 31days in May

Figure 4.2 shows the graphs of the mean hourly temperature over 24 hours for the three houses. The differences are particularly significant in the cold evenings and early mornings. The mean minimum indoor temperatures were lower (15.9°C) in the house made of stone compared with that of timber (17.8°C) and EPS (18.6 °C). During the warmest part of the day between 1200 noon and 2.00pm, the stone house was found to have a slightly higher indoor temperature (27.6°C) compared with that of timber (26.3°C) and EPS (27.2°C).

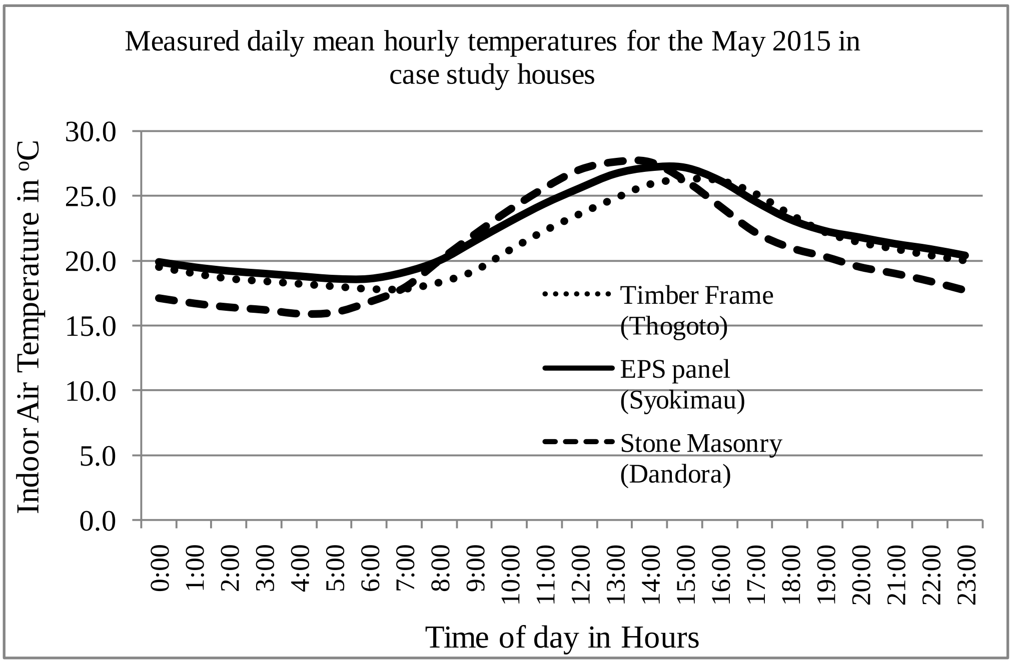


Figure 4.2 Mean hourly temperatures over 24 hours

Figures 4.3, 4.4 and 4.5 show the relationship between outdoor air temperature and indoor air temperatures measured every hour for 31 days of May 2015 for the three case houses.

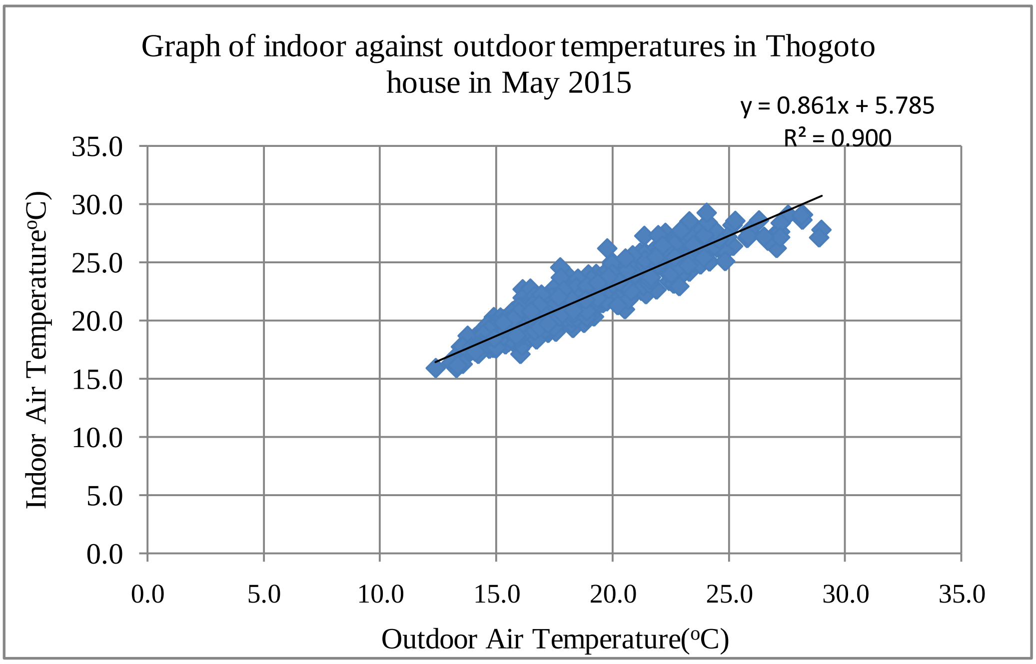


Figure 4.3 Graph of indoor and outdoor temperatures in Thogoto House

The regression equation is $T_i = 0.861T_o + 5.785$ (Figure 4.3) (eq. 4.1)

Where

T_i =indoor air temperature

T_o=outdoor temperature

R^2=0.900 (90% of the variation in the dependent variable (indoor temperature) is explained by the independent variable (outdoor temperature)).

Standard error is 0.96°C (the variation of the observed indoor temperatures about the regression line)

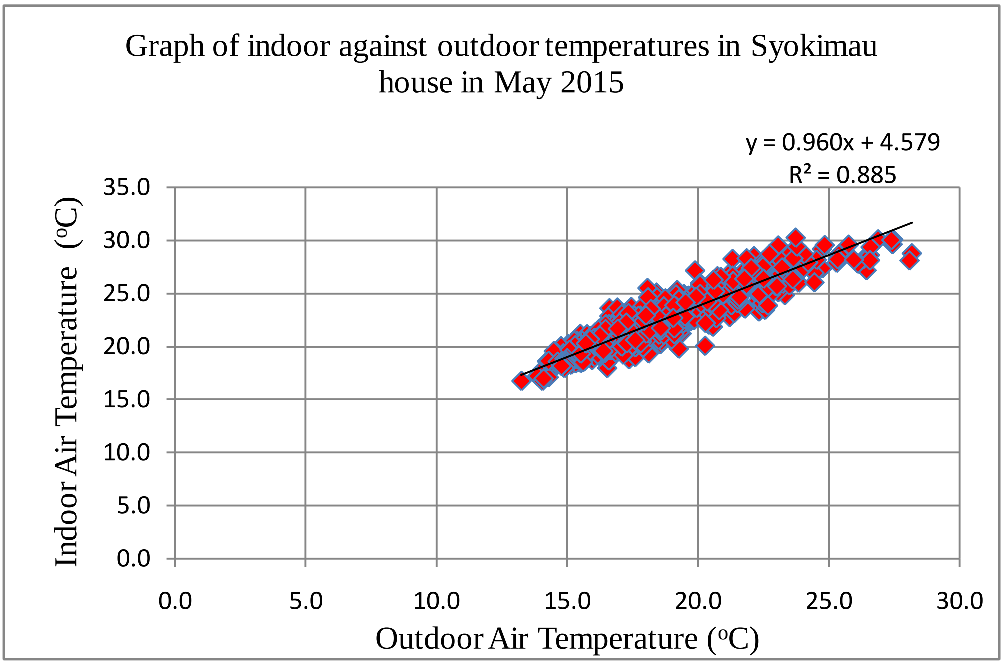


Figure 4.4 Graph of indoor against outdoor temperatures in Syokimau House.

$T_i = 0.960T_o + 4.579$ (eq. 4.2)

Where

T_i =indoor air temperature

T_o=outdoor temperature

R^2=0.885(88.5% of dependant variable (indoor air temperature) values can be explained by the independent variable (outdoor air temperature)).

Standard error is 1.04°C (the variation of the observed indoor temperatures about the regression line)

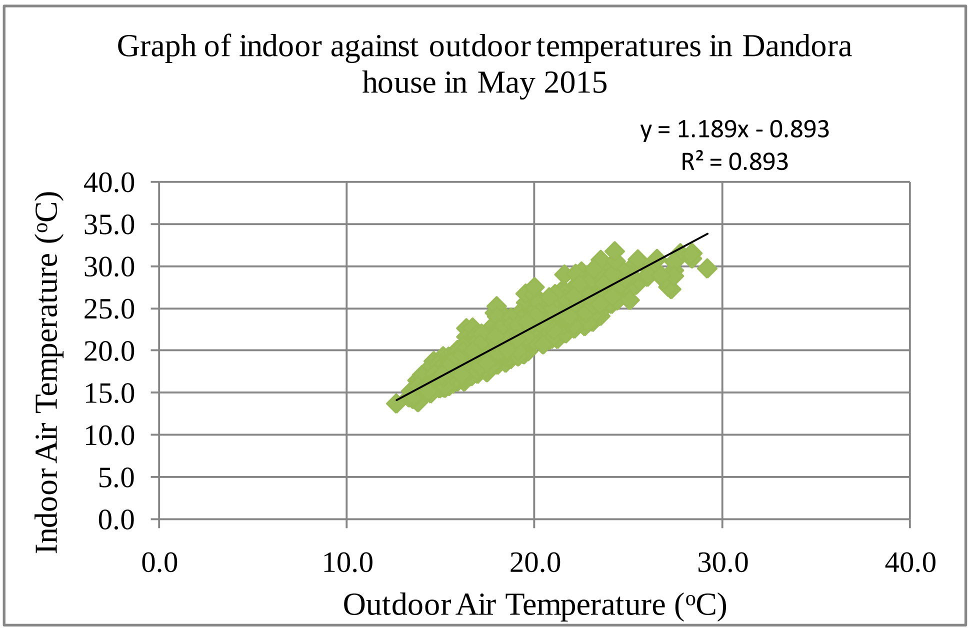


Figure 4.5 Graph of indoor against outdoor temperatures in Dandora House.

$T_i = 1.189T_o - 0.893$ (eq. 4.3)

Where

T_i =indoor air temperature

T_o=outdoor temperature

R^2=0.893 (89.3% of dependant variable (indoor air temperature) values can be explained by the independent variable (outdoor air temperature)).

Standard error is 1.37°C (the variation of the observed indoor temperatures about the regression line)

4.2.2 Building information and occupants details in case study buildings

The input data for thermal simulation was collected through observation and informal interviews with occupants. The required data was the number of occupants normally resident in the houses and the hours they typically spend in the living room, typical clothing, metabolic activities and the heat producing fittings and equipment.

Table 4.2 Data for thermal simulation from three case study houses

		Thogoto House		**Syokimau House**		**Dandora House**	
1	Area of living room	17 m^2		12 m^2		**11 m^2**	
2	Relative Humidity	65.8%		65.6%		**68.9%**	
3	Number of Occupants	7		4		**2**	
	Percentage occupancy over 24 hour period	Week Day	Week-end	Week Day	Week-end	Week Day	**Week-end**
	00.00 - 06.00 hrs	0%	0%	0%	0%	0%	**0%**
	06.00 - 07.00hrs	57%	29%	75%	50%	0%	**0%**
	07.00 - 16.00hrs	57%	86%	50%	100%	100%	**100%**
	16.00 - 19.00hrs	86%	100%	75%	100%	100%	**100%**
	19.00 - 24.00hrs	100%	100%	100%	100%	100%	**100%**
4	Clothing insulation	*0.17 m^2K/W*		*0.17 m^2K/W*		***0.17 m^2K/W***	
5	Metabolic heat gain (Seated, quiet)	58W per person =406W		58W per person 232W		**58W per person 116W**	
6	Heat gain due to lighting and equipment	Lighting	TV	Lighting	TV	Lighting	**TV**
		68W (75 W incandescent lamp)	50 W (32 inch CRT TV)	54W (60 W incandescent lamp)	50 W (32 inch CRT TV)	36W (40 W incandescent lamp)	**50 W (27 inch CRT TV)**
		Total 118W		Total 104 W		**Total 86W**	

Table 4.2 presents a summary of the findings of the building and occupant's information. The percentage occupancy figures represent the proportion of occupants in the living room to the total number of occupants resident in the houses. Between midnight and 6.00am in the morning, the living rooms were empty. The corresponding values for clothing insulation and metabolic heat gains were derived from ASHRAE Standard 55-2010 (Appendix 9). All the three houses use incandescent light bulbs whose output is about 90% heat and small television sets whose output is about 50 W (Kreider, Curtiss, & Rabl, 2010,). Relative humidity values were the average for the month of May as measured by the data loggers.

4.2.3 Calculation of the thermo-physical properties of walling materials

The calculation of the thermo-physical properties of various wall constructions in Nairobi in Table 4.3was done using density, thermal conductivity and specific heat capacities in ISO 10456(2007) and the formulae for calculating thermal transmittance and thermal mass values (Equations 2.4 and 2.5) .

Natural stone walls have generally similar thermal properties as concrete, fired clay and earth having thermal transmittance values about 3W/m^{2}K and thermal mass values of about 500KJ/m^{2}K (Figure 4.6). Timber walls have generally lower thermal transmittance values (2W/m^{2}K) and thermal mass values (30KJ/m^{2}K). EPS walls have the lowest transmittance values of the materials studied (0.35W/m^{2}K).

Galvanised corrugated iron sheet walls were found to have the highest transmittance values as well as the lowest mass values.

Table 4.3 Thermo-physical properties of typical walls in residential houses

Wall construction types		**Materials**	**Thermal conduct-ivity**	**Thermal trans-mittance**	**Specific heat capacity**	**Density**	**Thermal mass**
			W/mK	W/ m^{2}K	J/Kg/K	Kg/m^3	**J/m^{2}K**
1	Natural stone masonry	plaster	1.0	3.31	1000	1800	
		stone	1.8		1000	2400	**503,400**
2	Natural stone masonry	plaster	1.0		1000	1800	
		stone	1.8	3.17	1000	2400	**526,800**
		plaster	1.0		1000	1800	
3	GCI framed	GCI	50.0	5.62	450	7800	**10,125**
		cypress	0.12		1600	450	
4	GCI framed with lining	GCI	50.0	2.69	450	7800	**16,425**
		cypress	0.12		1600	450	
		gypsum board	0.21		1000	700	
5	Concrete block masonry	plaster	1.0	3.03	1000	1800	**566,800**
		concrete	1.65		1000	2600	
		plaster	1.0		1000	1800	
6	Fired clay brick masonry	plaster	1.0	2.48	1000	1800	**343,400**
		Fired clay	1.0		800	2000	
		plaster	1.0		1000	1800	
7	Stabilised rammed earth	plaster	1.0	2.21	1000	1800	**563,400**
		SRE	1.21		1000	1800	
		plaster	1.0		1000	1800	
8	Stabilised rammed earth	plaster	1.0	1.87	1000	1800	**743,400**
		SRE	1.21		1000	1800	
		plaster	1.0		1000	1800	
9	Timber frame with lining	Cypress board	0.12	1.76	1600	450	**29,772**
		cypress frame	0.12		1600	450	
		gypsum board	0.21		1000	700	
10	Timber frame. No lining	cypress board	0.12		1600	450	**23,472**
		cypress frame	0.12	2.90	1600	450	
11	150mm EPS panels	plaster	1.0		1000	1800	**128,900**
		EPS	0.03	0.39	1450	25	
		plaster	1.0		1000	1800	
12	240mm EPS panel	plaster	1.0	**0.32**	1000	1800	**295,625**
		EPS	0.03		1450	25	
		concrete	1.65		1000	2200	
		EPS	0.03		1450	25	
		plaster	1.0		1000	1800	

Source: ISO 10456 (2007) for density, thermal conductivity and specific heat capacity values

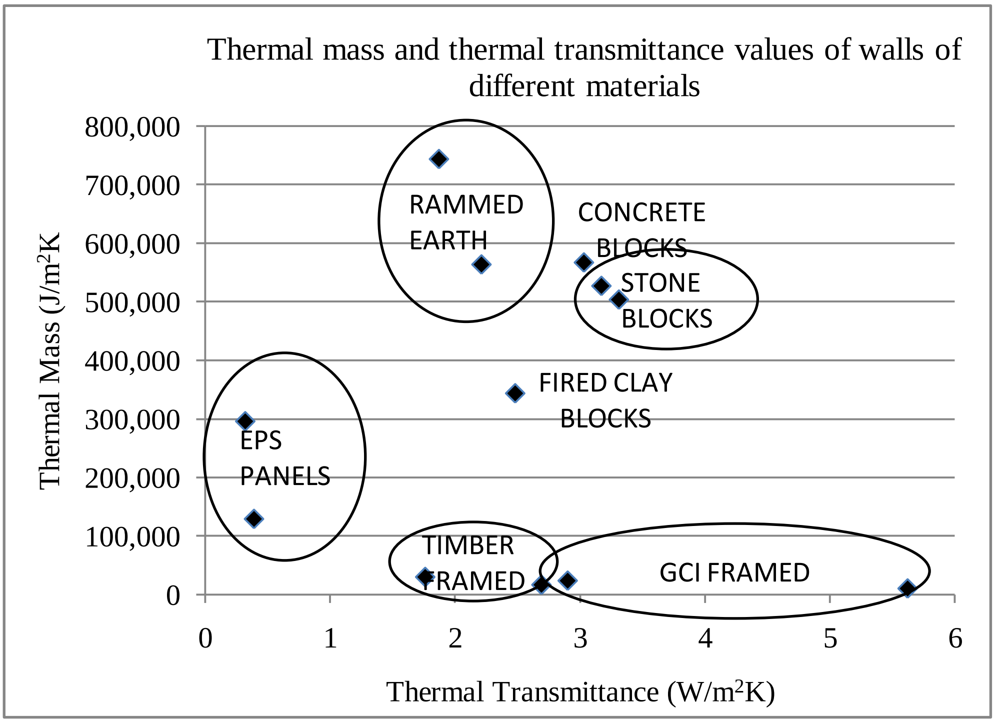


Figure 4.6 Mapping of thermal properties values of selected walls

4.2.4 Results of thermal simulation

The three case study houses were modeled in three dimensions (3D) from measured spatial data, the building materials ‘thermal properties and the occupancy data from Table 4.3 input into Autodesk Ecotect 2011 simulation software. The climatic data used is from the Dagoretti weather station in Nairobi.

The simulation considers one year hourly data for adaptive comfort range in Equation 2.10.For Nairobi, the comfort range was calculated from the monthly mean outdoor temperature of the coldest month (July: 15.7°C) for the lower limit and the hottest month (March:20.0 °C) for the upper limit. The thermal comfort range was between 19.2°C and 27.5°C.

Ecotect calculates the monthly loads of discomfort which are the degrees-hours when indoor temperatures are outside the comfort range. Figures 4.7 to4.12 show the Ecotect3D model and the graph of the monthly output for the timber (Thogoto), EPS panels (Syokimau) and stone (Dandora) .

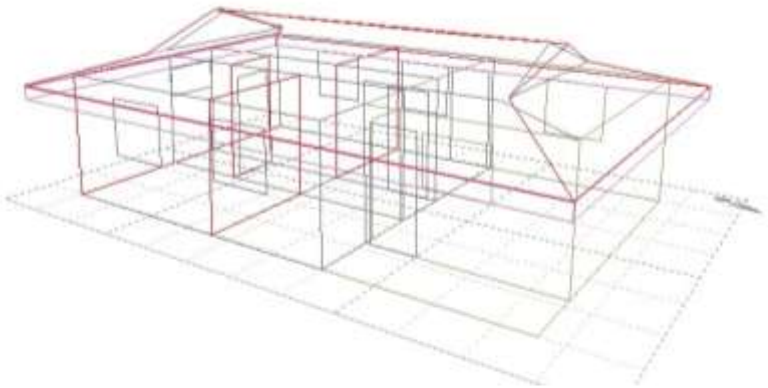


Figure 4.7 Ecotect Model of Thogoto House

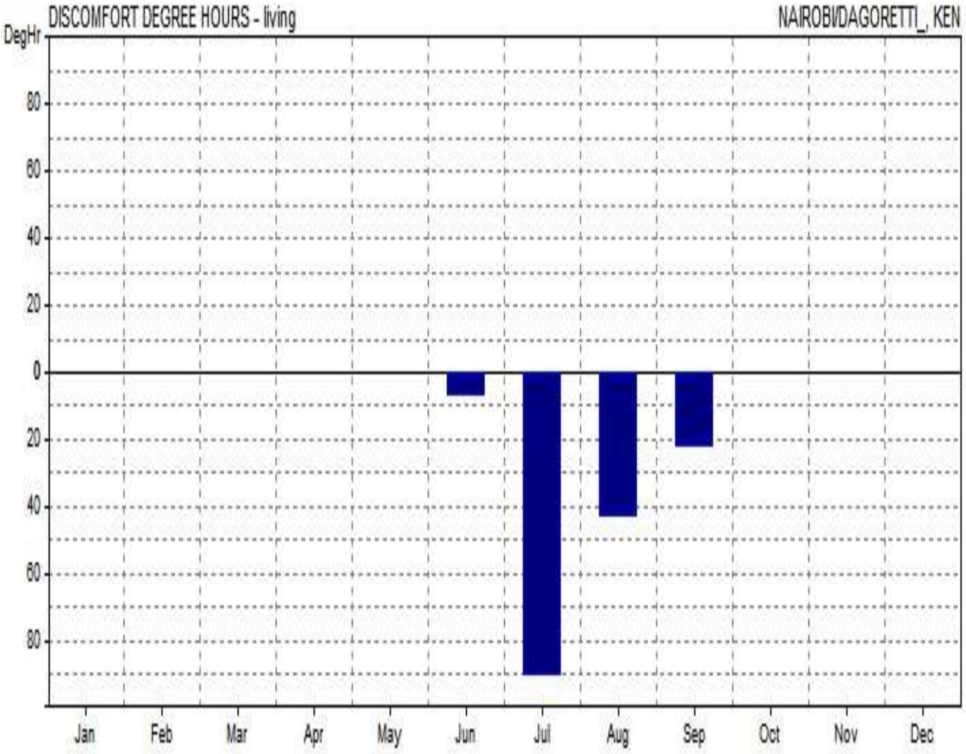


Figure 4.8 Discomfort levels for Thogoto House with timber frame walls

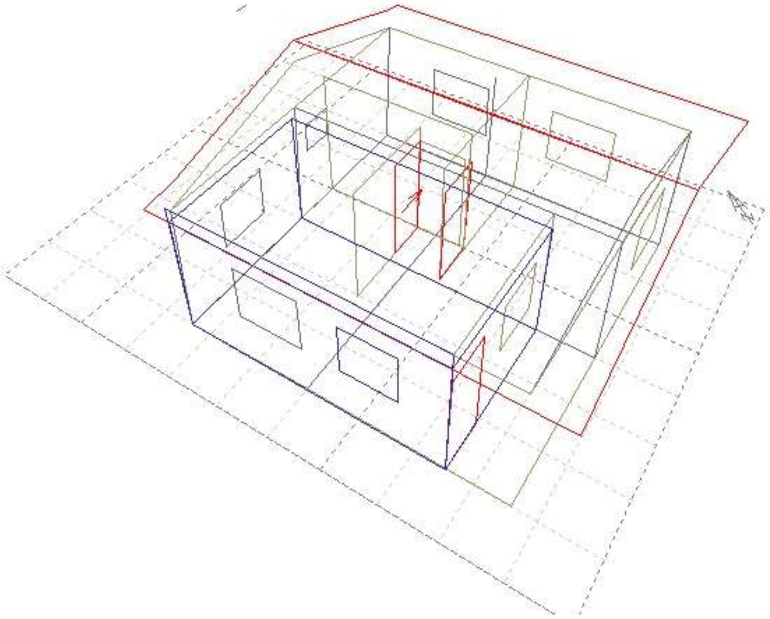


Figure 4.9 Ecotect Model of Syokimau House

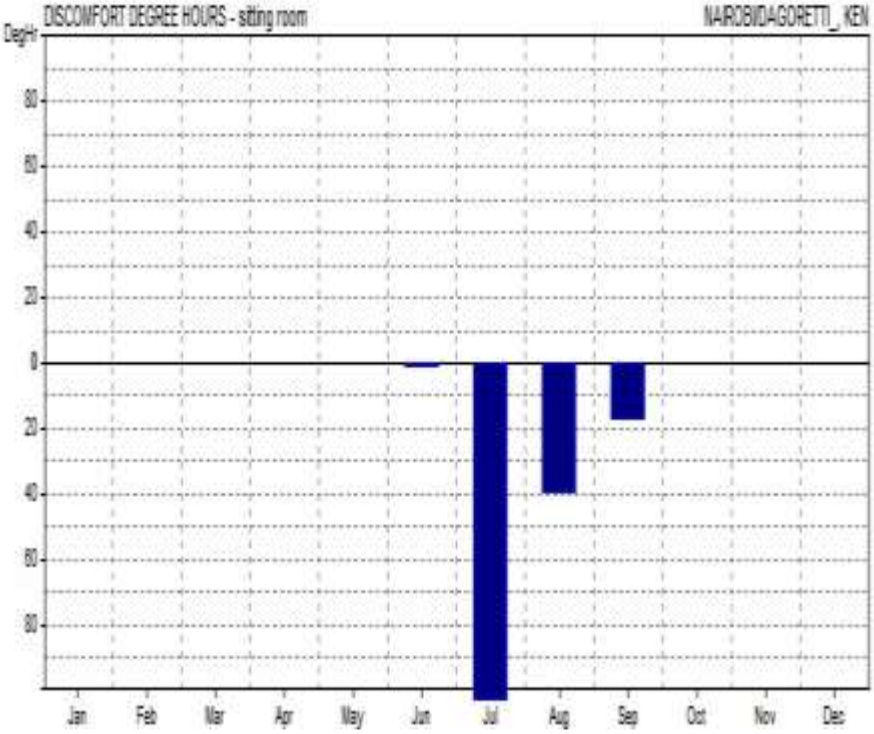


Figure 4.10 Discomfort Levels for Syokimau House with EPS panel walls

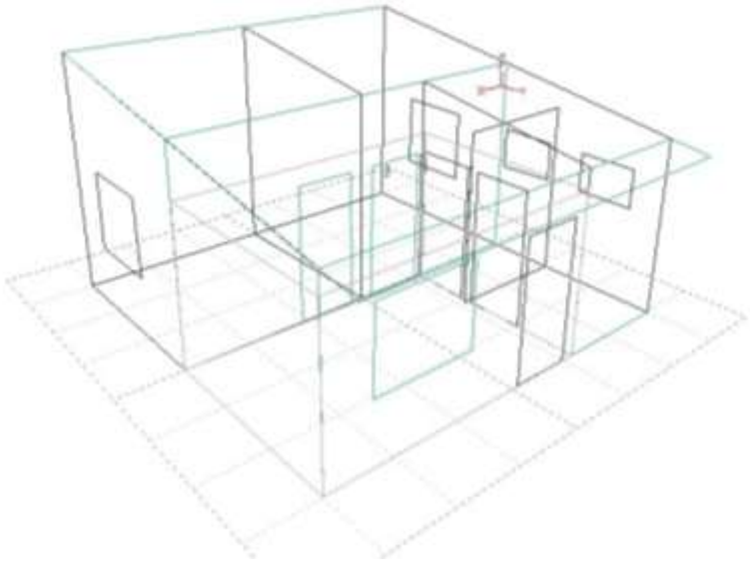


Figure 4.11 Ecotect Model of Dandora House

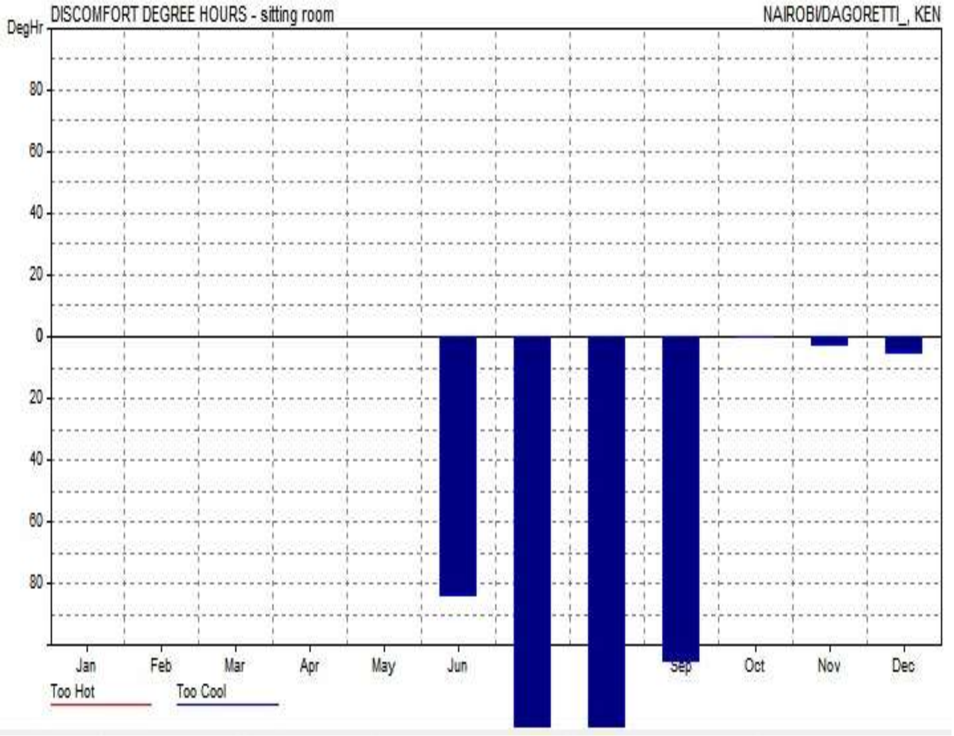


Figure 4.12 Discomfort Levels for Dandora House with natural stone walls

The walls were then varied for each of the twelve walls in Table 4.3 and for each of the three case houses. The results of annual discomfort for each of the twelve walls and the three houses are tabulated in Appendix 10, 11 and 12 and summarized in Table 4.4

Table 4.4 Thermal discomfort results from Ecotect software

	External wall description	**U-value**	**Thermal mass**	**Thermal discomfort (deg. Hours)**		
		W/m^{2}K	J/m^{2}K	Thogoto House	Syokimau House	**Dandora House**
1	Natural stone masonry wall	3.31	503,400	749.6	979.0	**916.2**
2	Natural stone masonry wall (rendered)	3.17	526,800	713.4	953.1	**860.0**
3	Galvanised corrugated iron (without lining)	5.62	10,125	1734.0	1826	**1897.2**
4	Galvanised corrugated iron(with lining)	2.69	16,425	474.9	769.4	**532.3**
5	Concrete blocks	3.03	566,800	575.3	1018.3	**769.2**
6	Fired clay bricks	2.48	343,400	292.4	713.1	**451.1**
7	Stabilized rammed earth (300mm)	2.21	563,400	180.0	661.5	**348.5**
8	Stabilized rammed earth(400mm)	1.87	743,400	87.9	590.2	**219.9**
9	Timber Frame(with lining)	1.76	29,772	164.4	470.8	**186.2**
10	Timber Frame (without lining)	2.90	23,472	461.6	666.7	**528.0**
11	Expanded polystyrene panels(single panel)	0.39	128,900	0.1	162.3	**5.1**
12	Expanded polystyrene panels (Double panel)	0.32	295,625	0.1	150.5	**9.5**

The relationship between the level of discomfort, the thermal transmittance and thermal mass was analysed using Microsoft Excel data analysis computer software tool. The summary output of the regression analysis is shown in Table 4.5

Table 4.5 Summary output for simple regression of thermal discomfort, thermal transmittance and thermal mass value

Regression Statistics	
Multiple R	0.9265
R Square	0.8585
Adjusted R Square	0.8499
Standard Error	187.4497
Observations	36.0000

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	-206.2041	79.2233	-2.6028	0.0137	-367.3852	-45.0230
X Variable 1 (U-value)	328.3606	23.4252	14.0174	0.0000	280.7016	376.0196
X Variable 2 (C-Value)	-0.0001	0.0001	-0.5497	0.5862	-0.0003	0.0002

The relationship between thermal discomfort, thermal transmittance and thermal mass for 36 observations is given by

$$DHc = 328.3606\,u - 0.0001c - 206.2041 \qquad (4.4)$$

Where

DHc= degree hours of discomfort in ^{o}C.Hrs

u = the thermal transmittance value of the external wall in W/m^{2}K

c = the thermal mass value of the external wall in J/m^{2}K

The results showed that the influence of thermal mass was insignificant in determining thermal discomfort (DHc)given the low coefficient (-0.0001)of X Variable 2(C-Value). In addition the p-value for X Variable 2(0.5862) is higher than 5%. P-value is defined as the probability of obtaining a result equal to what was actually observed (Hubbard, 2004). Traditionally, the threshold value or significance level of the test is 0.05 (Nuzzo, 2014). A large p-value (> 0.05) indicates weak evidence against the null hypothesis (There is no relationship between thermo-physical properties of building materials and the indoor thermal quality)

Further analysis relating thermal discomfort with thermal mass only and thermal discomfort with thermal transmittance are shown in linear relationship graphs in Figure 4.13 and Figure 4.14.

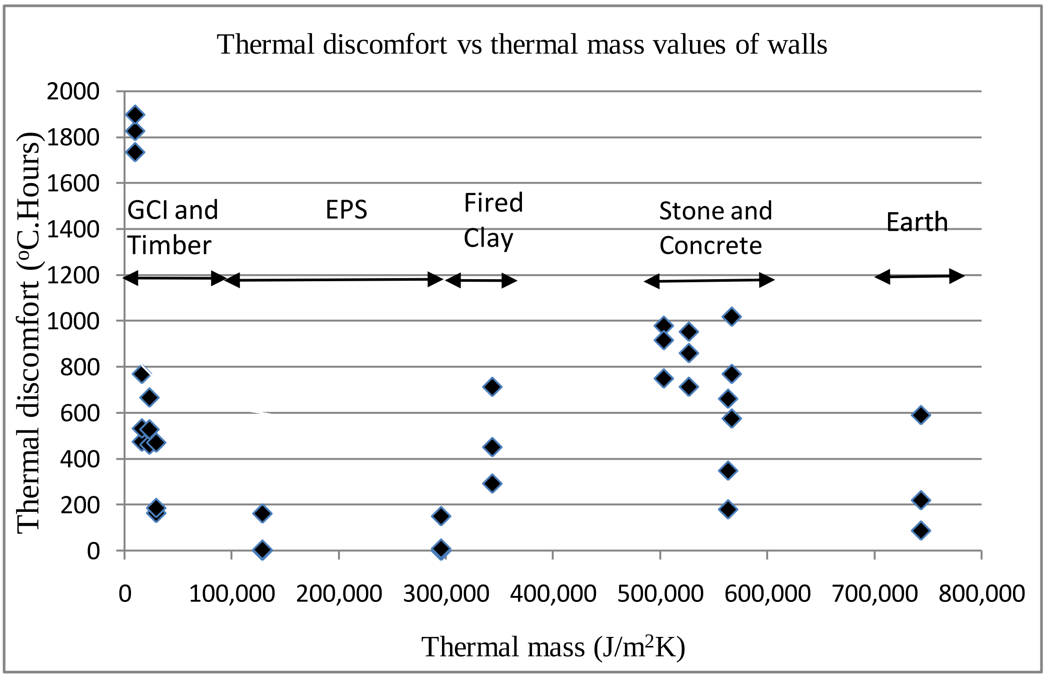


Figure 4.13 Mapping of thermal discomfort and thermal mass values of walls

There was no evident relationship between thermal discomfort and thermal mass of walls. Walls of different materials but with similar thermal mass were found to result in different thermal discomfort levels (Figure 4.13). Buildings with timber walls with thermal mass ranging from 20,000 to 30,000 J/m^{2}K had similar thermal discomfort levels with earth walls with much higher thermal mass (560,000 to750,000 J/m^{2}K).

On the other hand, thermal discomfort was found to increase with increasing thermal transmittance of walls (Figure 4.14).EPS walls with the lowest thermal transmittance of 0.3 to 0.4W/m^{2}K had the lowest thermal discomfort (0-200^{o}C hours). GCI walls with the highest thermal transmittance (5.0 to 6.0W/m^{2}K) had the highest thermal discomfort (1700-1900^{o}C hours).

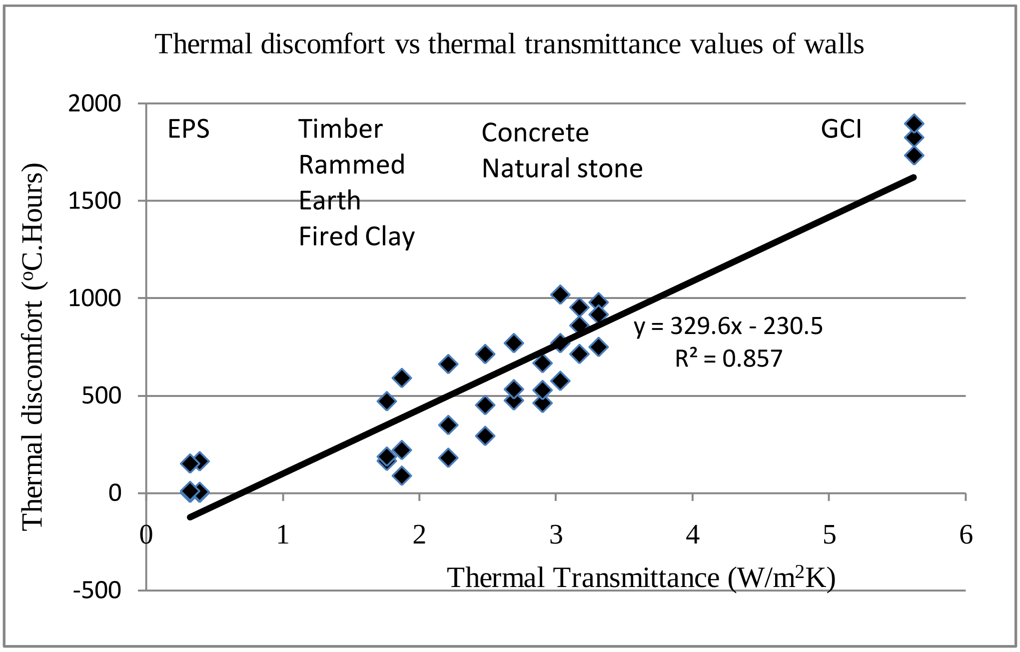


Figure 4.14 Relationship between thermal discomfort and thermal transmittance of walls

Table 4.7 shows a summary output for simple regression of thermal discomfort and thermal transmittance values (U-values).The low *p*-value (lower than a significance level of 0.05) suggests that the observed data are inconsistent with the assumption that the null hypothesis is true and therefore that hypothesis must be rejected. The alternative hypothesis is that there is a relationship between thermo-physical of walls and thermal discomfort.

Table 4.6 Summary output for simple regression of thermal discomfort and thermal transmittance

Regression Statistics	
Multiple R	0.9258
R Square	0.8572
Adjusted R Square	0.8530
Standard Error	185.5161
Observations	36.0000

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	***Upper 95%***
Intercept	-230.5346	65.0289	-3.5451	0.0012	-362.6892	**-98.379**
X Variable 1 (U-Value)	329.6027	23.0755	14.2837	0.0000	282.7077	**376.497**

The relationship between thermal discomfort and thermal transmittance is described by a linear regression equation:

$$DHc = 329.6027u - 230.5346 \qquad (4.5)$$

Where:

DHc = degree hours of discomfort in degree hours

u = the thermal transmittance of the external wall in W/m^{2}K

R^2=0.857 (85.7% of dependant variable (thermal discomfort) values can be explained by the independent variable (thermal transmittance values)).

Standard error is 185.5^{o}CHrs (the variation of the observed thermal discomfort about the regression line)

Given DHc = 329.6027u - 230.5346

When

DHc = 0 (no thermal discomfort),
u= 0.6994

Therefore, to achieve zero level of discomfort, the thermal transmittance value (U-Value) should be a maximum of **0.70 W/m^{2}K.** Of the twelve walls tested in the simulation, only expanded polystyrene wall panels (0.32-0.39 W/m^{2}K) were below this maximum value

4.3 Discussion

4.3.1 Indoor temperatures measured in Nairobi

The actual measurements of air temperature in various houses provide an insight into the nature of indoor thermal environment in residential houses in Nairobi. While the three houses studied are similar in many respects, there are still differences in occupancy, room size and heat gain that make actual comparison of the houses difficult. Such a comparison is best done using simulation so that other parameters other than the walls are kept constant.

Air temperature alone does not normally constitute all necessary criteria for human thermal comfort. The other parameters are radiant temperature, humidity, air velocity clothing insulation and metabolic rate. However ASHRAE Standard 55 (2010) allows for the assumption that operative temperature approximately equals air temperature when there is no radiant and/or radiant panel heating or radiant panel cooling system, no major heat generating equipment in the space, where windows are shaded and no forced air movement, and when occupants are engaged in nearly sedentary activities. These are the conditions in the case study houses.

Figure 4.15 shows the mean hourly indoor air temperature over 24 hours for the three houses. Assuming air temperature approximately equals operative temperature the lower and upper limits of comfortable temperatures (19.8^{o}C and 26.8^{o}C) are calculated from the adaptive thermal comfort formula (Equation 2.10). It is evident in the graph (Figure 4.15) that air temperatures are below the comfort zone for significant periods compared to the brief period around midday when air temperatures exceed the comfort levels. This suggests discomfort due to cold is more critical for Nairobi. The degree of discomfort due to cold is the area of the line graph below the lower limit. The living room of the EPS house is least uncomfortable with 5.8 degree hours of cold discomfort per day compared to 13.2 and 30.0 for the timber house and stone house respectively

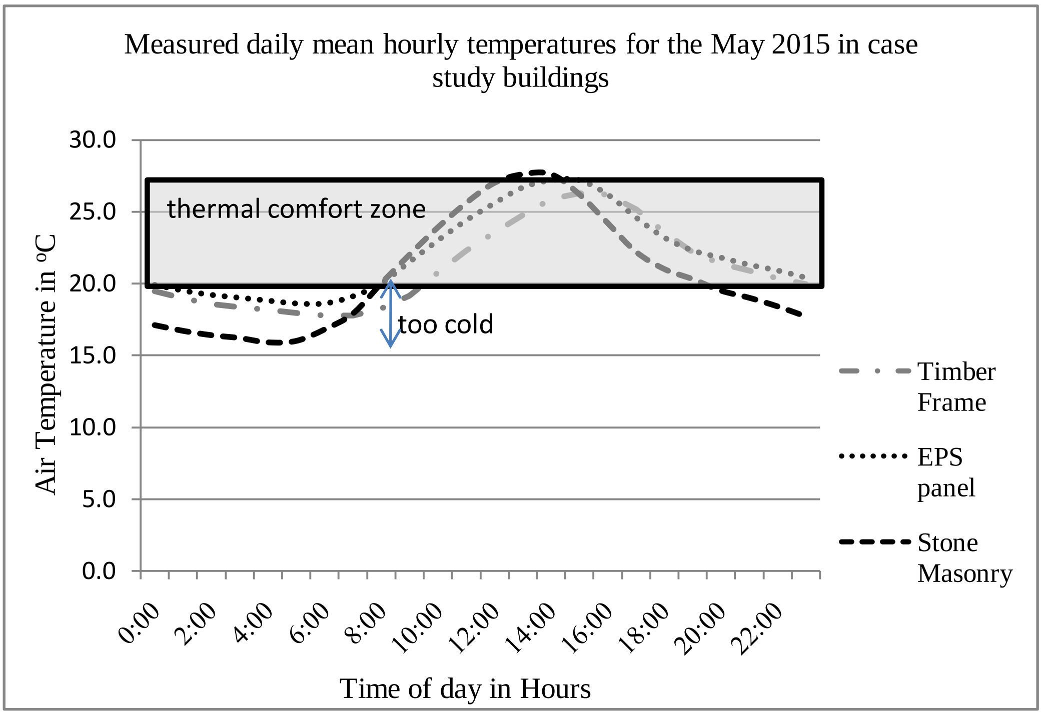


Figure 4.15 Daily thermal discomfort in the living room of case buildings

Significantly, the measurements for the stone house (Dandora house) suggest that inhabitants of masonry stone houses which constitute almost half (47.4%) of all residential houses in Nairobi would require heating at night and early mornings to achieve thermal comfort in May and the colder months of June, July and August to achieve thermal comfort.

These findings are consistent with the reports from the Kenya Meteorological Services (2015) that during the months of June to September, day temperatures remain low and occasionally the maximumdoes not exceed 18° C. Temperatures as low as 8° C or even 6° C are recorded at night and early morning resulting in people resorting to light fires in their homes. This presents safety concerns in houses due to dangers of house fires and economic and environmental costs of burning fuels.

Using the linear equations 4.1, 4.2, and 4.3 it is possible to predictindoor temperatures given the outdoor temperature values from Nairobi's climatic data (Table 4.7).From the calculations it is evident that a stone house is likely recorded the lowest indoor temperature of the three buildings.

Table 4.7 Prediction of indoor temperature in case houses using equations 4.1, 4.2 and 4.3

			THOGOTO	**SYOKIMAU**	**DANDORA**
Outdoor Air Temperatures(^{o}C)			Timber Frame $T_i = 0.861T_o + 5.785$	EPS Panel $T_i = 0.960T_o + 4.579$	**Masonry stone** **$T_i = 1.189T_o - 0.893$**
1	Monthly mean	17.7	21.0	21.6	**20.2**
2	Monthly mean maximum	24.1	26.5	27.7	**27.8**
3	Monthly mean minimum	14.2	18.0	18.2	**16.0**

4.3.2 Building information and occupants details

The findings of the three cases reveal that the living rooms have the highest levels of occupation in the period between early evenings and sleeping time between 19.00 hours and midnight. During the day, some of the building occupants are away in school and places of work on weekdays. Between midnight and 06.00 hours, occupants are asleep in the bedrooms. The period of occupancy in the living rooms is therefore 18 hours. This results in reduction of overall thermal discomfort in the living room as inhabitants retire to bedrooms to sleep under insulation cover of blankets during the coldest part of the night.

When period of actual occupation are taken into account, the level of thermal discomfort reduced as shown in Figure 4.16 and Table 4.8

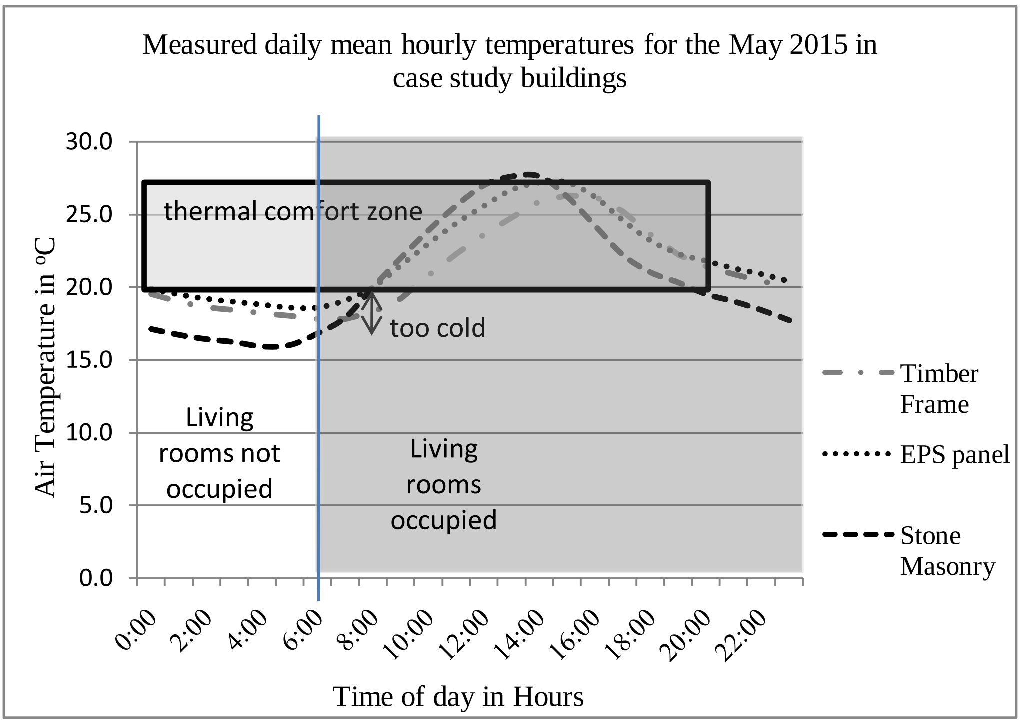


Figure 4.16 Thermal discomfort levels during18 hours of occupancy in the living room of case houses

Table 4.8 Thermal discomfort in living rooms of case study houses in May

		Thermal Discomfort (^{o}C.Hrs)		
	Period	Timber Frame	EPS Panel	Masonry stone
1	24 hour period	13.2	5.8	30.0
2	18 hour period (actual occupancy)	6.1	1.9	9.5

4.3.3 Thermo-physical properties of walls

The findings of the thermo-physical properties (Table 4.3) show that some minor changes in wall specifications can significantly alter the thermal transmittance values of walls. Table 4.9 shows that in framed walls, addition of 9mm gypsum plasterboard as internal lining in timber and galvanised corrugated walls lowers their thermal transmittance values by 39% and 52% respectively.

Table 4.9 Effects of internal lining on thermal transmittance of framed walls

Wall Description	**Thermal transmittance (U) values in W/m^{2}K**		
	Without internal lining	With 9mm thk plasterboard	Percentage change
Timber weatherboards on timber framework	2.9	1.76	39.3%
Galvanized corrugated iron sheets on timber framework	5.62	2.69	52.1%

The results of the simulation show significant change in thermal transmittance of concrete when before and after insulation. Addition of expanded polystyrene to concrete panels reduces thermal transmittance values by almost 89% with only a minimal increase in weight of the wall (Table 4.10).

Table 4.10 Effect of insulation on thermal transmittance of concrete walls

	Thermal transmittance (U) values in W/m^{2}K		
	Without insulations	With 100mm EPS insulation	**Percentage change**
Concrete wall	3.03	0.32	**89.4%**

4.3.4 Results of thermal simulation

The results of the simulation and the regression Equation 4.3 show that thermal transmittance is more important than thermal mass in predicting the indoor thermal environment in the area of the study. Thermal mass property enables the building envelope to store heat during periods of heat gain such as due to solar radiation and release it later in the colder hours of the day.

The results also show that discomfort is mostly experienced during the cold months of June, July, August and September (Figures 4.8, 4.10, 4.12 and Appendices K, L and M). The differences in performance of the studied building materials are due to their impact during those months.Thermal insulation due to low transmittance enables heat generated inside the building to be retained and not transferred to the colder outdoors.

The significance of insulation is consistent with international practice of using thermal transmittance values (U-values) in regulations concerning the building envelopes. Table 4.11 shows the maximum thermal transmittance values allowed in selected cities. The maximum U- values allowed are lower in colder areas compared to warmer areas.

Table 4.11 Maximum thermal transmittance of walls for selected cities

City	**Mean monthly temperature values**	**Maximum U-value for walls (W/ m^{2}K)**
London, United Kingdom	6.8°C – 19.6°C	0.25
Johannesburg, South Africa	9.6°C – 19.5°C	0.46
Tokyo, Japan	6.0°C – 27.5°C	0.53
New York, United States	0.3°C – 24.7°C	0.80
Nairobi, Kenya (proposed)	15.7°C- 20.0 °C	0.70

Sources: NOAA (2013).The Building Regulations 2010 (2010), SANS 204 (2011), IEA(2008), IECC (2004)

Previous studies of materials with differences in thermal transmittances tend to support the contribution of thermal transmittance values. Palme, Guerra and Alfaro (2014) studied houses with 500mm thick rammed earth walls (1.3 W/m^{2}K) wooden walls (1.6 W/m^{2}K) adobe walls (1.7 W/m^{2}K) and concrete walls (3.5 W/m^{2}K) in Chile. Earth and wooden walls performed better than concrete walls. However, Heartcote and Moor (2007) studied mud bricks (1.54 W/m^{2}K), insulated panels (0.21 W/m^{2}K) and insulated clay walls (0.53 W/m^{2}K) in Australia but concluded that thermal transmittance values did not adequately predict thermal performance. Despite this, the Building Code of Australia (BCA), provides regulations for walls based on thermal transmittance (Shui, Evans &Somasundaram, 2009, Table 5)

4.3.5 Comparison of measured and simulated data

The temperature measurements in the case houses are meant to compare and verify comparable simulation outputs by Ecotect.

i. Outdoor temperature differences

The differences in outdoor temperatures are summarized in Table 4.12.Ecotect simulation outdoor temperature data was the climatic values for Dagoretti weather station whereas the case studies were taken from different other parts of Nairobi. Local variations are expected with higher temperatures in the lower altitude areas to the south of Nairobi(such as Syokimau) and more densely built-up areas in the east (such as Dandora).

Table 4.12 Differences between outdoor measured and climatic temperatures

		Thogoto House		Syokimau House		Dandora House	
	Nairobi Climatic Temperature	Measured	Difference	Measured	Difference	Measured	Difference
Mean outdoor temperature	17.7	17.9	-0.2	18.2	-0.5	18.1	-0.4
Maximum outdoor temperature	19.4	19.9	-0.4	20.0	-0.6	20.1	-0.7
Minimum outdoor temperature	16.3	15.7	0.6	16.2	0.1	15.9	0.4
Outdoor temperature range	3.2	4.2	-1.0	3.8	-0.6	4.3	-1.1

In addition climatic data is as a result of averaging over many years which results in moderation of extreme values that may be measured from time to time. The daily range of outdoor temperatures is therefore higher when measured compared to those from climatic data. The differences between outdoor temperature range measured and climatic values are 1.0°C, 0.6°C and 1.1°C for Thogoto, Syokimau and Dandora respectively.

ii. Indoor temperature differences

As would be expected, the differences in outdoor temperatures in Table 4.12 will result in differences in the resultant indoor temperatures from measurements compared to simulation. Ecotect indoor temperature output is operative temperature whereas the actual measurements were air temperature values. The simulation values were therefore slightly modified to incorporate radiant temperature, air velocity, humidity, clothing and metabolic rate. Table 4.13 shows the comparisons for indoor temperatures.

Despite the differences, the thermal discomfort values from Ecotect for timber walls (Thogoto House), EPS walls (Syokimau House) and stone walls (Dandora House) show that of the three, EPS was the best performing, followed by timber. The stone house was the most uncomfortable. This was consistent with the findings of actual temperature measurements.

The thermal simulation by Ecotect uses temperature measurements that have been observed over a long period (climatic data) and outputs thermal discomfort loads that incorporate other parameters essential for the overall determination of thermal comfort: air temperature, radiant temperature, air velocity, humidity, metabolic activity and clothing insulation.

Table 4.13 Difference between indoor simulated and measured temperatures in Thogoto House

	Measured Temperature (°C)	**Simulated Temperature (°C)**	**Difference (°C)**
Mean Indoor temperature	21.2	20.9	**0.3**
Maximum indoor temperature	22.7	22.2	**0.5**
Minimum indoor temperature	19.4	20.3	**-0.9**
Indoor Temperature Range	3.3	1.9	**1.4**

Table 4.14 Differences between indoor simulated and measured temperatures in Syokimau House

	Measured Temperature (°C)	**Simulated Temperature (°C)**	**Difference (°C)**
Mean Indoor temperature	22.0	21.1	1.0
Maximum indoor temperature	23.6	22.8	0.8
Minimum indoor temperature	20.2	20.3	-0.1
Indoor Temperature Range	3.4	2.5	0.9

Table 4.15 Difference between indoor simulated and measure temperatures in Dandora House

	Measured Temperature (°C)	Simulated Temperature (°C)	**Difference (°C)**
Mean Indoor temperature	20.6	20.2	**0.5**
Maximum indoor temperature	22.7	21.3	**1.5**
Minimum indoor temperature	18.0	19.5	**-1.5**
Indoor Temperature Range	4.7	1.8	**2.9**

4.3.6 Achieving U-Value equal or less than $0.70 W/m^2K$ in walls

Of the twelve wall assemblies studied in the research, only those with expanded polystyrene insulation achieved requirement for thermal comfort. Through addition of light weight insulating materials such as foamed polymers, foamed glass or mineral fibres that have thermal conductivities of 0.03-0.04 W/mK, it is possible to reduce the thermal transmittance values of the wall constructions in Nairobi to $0.70 W/m^2K$

The maximum value of thermal transmittance (U) for thermal comfort was found to be $0.70 W/m^2K$.

From the formula:

$$U = \frac{1}{TotalResistances\, of wallcomponents\ (R)}$$

$$R = \frac{1}{U}$$

Therefore the minimum total thermal resistances of the wall components (R) for comfort is = $1/0.70\ W/m^2K$

= $1.43\ m^2K/W$

Table 4.14 shows the required thickness of thermal insulation materials with thermal conductivity of 0.04 W/mK (thermal resistivity =25mK/W) to achieve a thermal resistance of $1.43 m^2K/W$ in natural stone wall and timber framed wall.

Table 4.16 Thickness of insulating material required to achieve thermal transmittance of $0.7 W/m^2K$

	Thermal transmittance (U-Value) W/m^2K	**Total resistance (R-Value) m^2K/W**	**Additional resistance to achieve $1.43 m^2K/W$**	**Required thickness of material with 25 mK/W**
Stonewall	3.31	0.30	1.13	0.045
Timber framed wall	1.76	0.57	0.86	0.034

Thermal insulating materials for buildings may also be derived from agricultural waste providing a sustainable source for an agricultural based economy like Kenya.

Insulation boards made of rice husks have been found to have thermal conductivity as low as 0.022W/mK (Bhatti et al., 2011)

Low thermal transmittance may also be achieved by using masonry blocks of lightweight concrete (Table 4.17) with thermal conductivity of 0.16W/mK (Resistivity = 6.25mK/W).

Table 4.17 Thermal transmittance for lightweight concrete block wall

	Thickness (m)	**Material / Surface**	**Resistivity (mK/W)**	**Resistance (m2K/W)**
R_{so}		Outside surface resistance		0.04
R_1	0.013	Cement/ sand plaster	1.00	0.013
R_2	0.200	Light weight concrete	6.25	1.25
R_3	0.013	Cement/ sand plaster	1.00	0.013
R_{si}		Inside Surface resistance		0.13

Using Equation 2.4

$$U = \frac{1}{(0.04 + 0.13 + 0.013 + 1.25 + 0.013)} = 1/1.446 = 0.69\text{W/m}^2\text{K}$$

U- Value for 200mm plastered lightweight concrete block=0.69W/m^{2}K.

4.4 Summary

This chapter presented the data collected and discussions from results of case and computer thermal simulation. The temperature measurements showed that the mean indoor temperature was higher (22.0°C)in the house made of expanded polystyrene (EPS) panels compared with that of timber (21.2°C) and stone (20.6 °C). The EPS panel house had an overall higher difference (3.8°C) between the indoor and outdoor mean temperatures than the other two houses(3.3°C and 2.5°C respectively).

The results of thermal simulation using Ecotect software showed that thermal transmittance values of walls have significant direct linear relationship with thermal discomfort and that the influence of thermal mass of walls was negligible. To achieve thermal comfort in living rooms during the hours of occupancy between 6.00am in the morning to 12.00 midnight, the maximum thermal transmittance value of external walls was found to be 0.70 W/m^2K.

Thermal transmittance values may be achieved by addition of light weight insulating materials such as foamed polymers, foamed glass, mineral fibres and agricultural fibres to traditional materials such as stone, concrete or timber. Masonry blocks of lightweight concrete with plaster were found to also achieve the required thermal transmittance value for thermal comfort in Nairobi.

CHAPTER FIVE
CONCLUSIONS AND RECOMMENDATIONS

This chapter presents a summary of the objectives, literature review, methodology and the findings that constitute this thesis. It also contains the conclusions and recommendations.

5.1 Summary

The aim of this thesis was to determine the thermo-physical properties of walls of residential buildings in Nairobi that would achieve human thermal comfort without artificial heating and cooling. Provision of healthy and comfortable indoor environment through passive means is necessary for sustainable buildings to save energy that would otherwise be required for heating or cooling.

In Kenya the regulations regarding walls in buildings do not set any requirement regarding thermal performance despite temperatures falling to below 10^oC in the highland areas during the cold season. The international trend is to specify the thermo-physical properties, usually the maximum thermal transmittance (U-value) of the elements of the building envelope.

Measurements of indoor and outdoor temperature were taken from three cases of residential buildings with different wall materials in Nairobi in the month of May. The walls were of natural stone, timber and expanded polystyrene (EPS). The indoor air temperatures in the living room of the three buildings were compared. The three cases were then modelled using the Autodesk Ecotect 2011 thermal simulation software. Input data included the Nairobi climatic data, spatial dimensions of space of interest, construction materials, human activities, type clothing worn, climatic data, indoor relative humidity and type of heat producing equipment. The external walls of the case study buildings were varied to study the effect of different wall materials. The thermal transmittance values and thermal mass values of walls were calculated for natural stones, galvanized iron sheets, concrete, fired clay, stabilized earth, timber and expanded polystyrene panels (EPS).

The Ecotect software calculates indoor temperatures given the external climatic data, indoor occupant’s activities and thermo-physical properties of building materials.

Using the adaptive formula of thermal comfort, the level of thermal discomfort in each of the houses constructed with the different materials is determined. The relationship between thermal discomfort and thermo-physical properties of the building materials is used to establish which properties affect thermal discomfort.

From study measurements, the living room of the house made of EPS was found to be warmer having a higher mean indoor temperature of 3.8^{o}C above the mean outdoor temperature compared to timber (3.3^{o}C) and stone (2.5^{o}C). The higher indoor temperatures are desirable in Nairobi where outdoor temperatures are low and the main concern is cold discomfort. Through computer simulation, the thermal transmittance of the walls was found to have a more significant effect on thermal discomfort compared to thermal mass. The maximum thermal transmittance (U-Value) for zero thermal discomfort was 0.70W/m^{2}K.

The required thermal transmittance values may be achieved by addition of light weight insulating materials such as foamed polymers, foamed glass, mineral fibres and agricultural fibres to traditional materials such as stone, concrete or timber. Masonry blocks of lightweight concrete with plaster were found to also achieve the required thermal transmittance value for thermal comfort in Nairobi.

5.2 Conclusions

The following conclusions are drawn from the research:

1. The living room of the house made of EPS was found to have a higher mean indoor temperature of 3.8^{o}C above the mean outdoor temperature compared to timber (3.3^{o}C) and stone (2.5^{o}C). The resulting lower indoor temperature in the living room of the house made of stone suggests that inhabitants of similar stone houses in Nairobi experience cold discomfort during the month of May and the other colder months of June to September.

2. Thermal transmittance of walls was found to have a more significant effect on thermal discomfort compared to thermal mass.The maximum thermal transmittance value for thermal comfort in residential houses that are naturally conditioned in Nairobi was found to be 0.70 W/m^{2}K.This value may be achieved through addition of expanded polymers, mineral wool or

agricultural fibres to the traditional masonry or framed walls or using lightweight plastered concrete blocks of at least 200mm thickness.

5.3 Recommendations

The recommendations drawn from the conclusions are:

1. Thermal analysis at the building design stage be emphasized as part of the design process by architects and engineers to ensure that buildings are designed with comfortable indoors through passive means and if necessary specify appropriate interventions by heating.
2. Thermal performance to be incorporated as an important criterion in building materials research with greater emphasis of thermal insulation in cool tropical climatic areas.
3. Regulatory authorities to incorporate maximum thermal transmittance requirements for building elements in building regulations. For walls $0.70 W/m^2K$ is recommended for single storey residential houses in Nairobi.

5.4 Areas for further research

The following areas of further research in thermal comfort and specification of building materials for thermal performance are proposed:

1. Research into level of satisfaction of building users with indoor thermal environment in the tropical highland areas of Africa since the available formulae are based on studies carried out in other continents.
2. Research on local sustainable materials in Kenya that have potential of increasing thermal insulation such as agricultural waste.
3. Research on the impact of climate change on indoor thermal conditions.
4. The social acceptability and cost implications of new materials such as expanded polystyrene panels in a market dominated by stone as a major building material.

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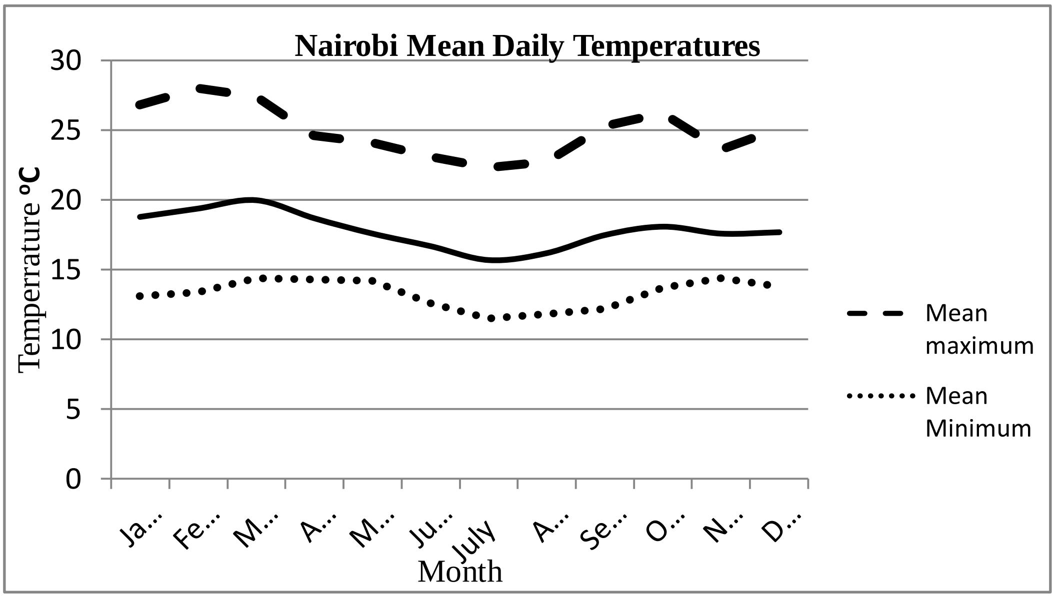
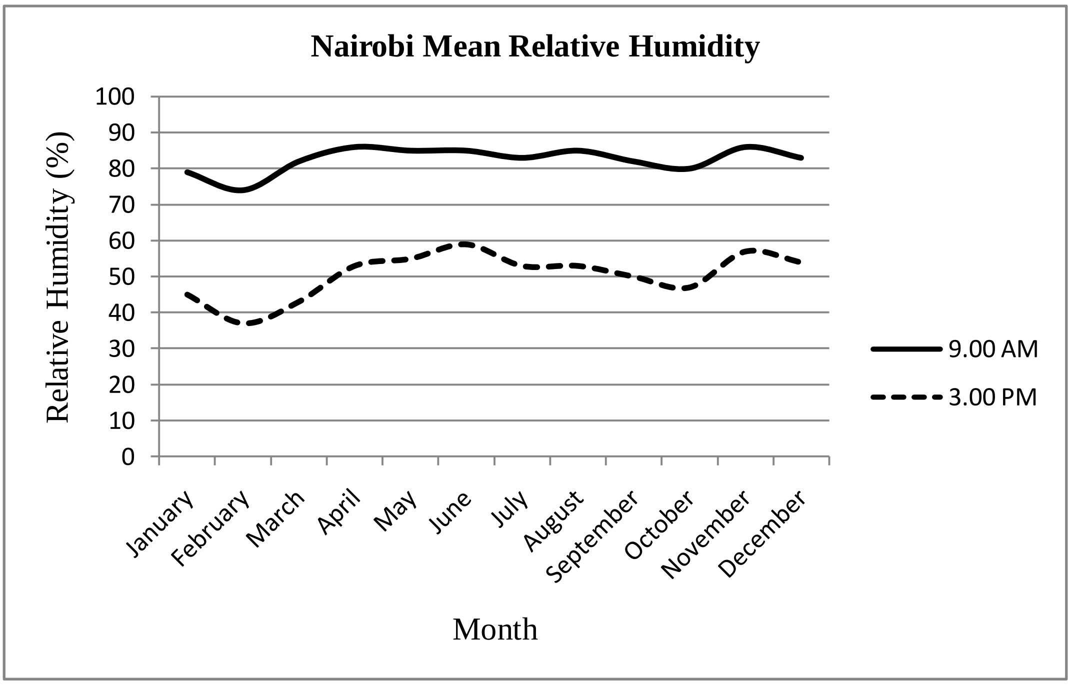
APPENDICES

Appendix 1: Temperature and humidity data for Nairobi



Source: Kenya Meteorological Services (2015)



Source: Kenya Meteorological Services (2015)

Appendix 2: Data Logger Set-Up in Case Study Houses

External air temperature probe outside Thogoto timber framed house

Internal air temperature and humidity sensor attached to ceiling in Thogoto house

External air temperature probe outside Dandorastone house

Internal air temperature and humidity sensor attached to ceiling in Dandorahouse

External air temperature probe outside SyokimauEPS panel house

Internal air temperature and humidity sensor attached to ceiling in Syokimauhouse

Appendix 3: Mean Hourly temperature for month of May: Thogoto House

THOGOTO HOUSE			
	Measured Mean Daily Temperature		
Date in May	**Measured Indoor**	**Measured outdoor**	**Range**
1	21.2	18.2	3.0
2	20.7	17.6	3.1
3	20.8	18.3	2.6
4	20.3	16.6	3.6
5	21.2	18.3	3.0
6	21.0	17.9	3.1
7	21.4	18.0	3.5
8	20.8	17.8	3.0
9	21.8	18.6	3.1
10	21.5	18.2	3.4
11	21.5	18.5	3.1
12	21.5	18.7	2.8
13	22.0	19.1	2.9
14	22.7	19.9	2.8
15	22.3	19.2	3.0
16	21.8	18.7	3.1
17	21.9	18.2	3.7
18	21.7	18.3	3.4
19	21.4	17.9	3.5
20	21.2	18.1	3.2
21	21.7	18.1	3.6
22	21.2	17.7	3.5
23	20.8	17.1	3.7
24	20.8	17.4	3.4
25	20.9	17.0	3.8
26	21.6	17.7	3.9
27	20.6	17.7	3.0
28	20.6	16.9	3.7
29	20.0	16.4	3.7
30	19.4	15.7	3.7
31	20.1	16.6	3.4
MEAN	21.2	17.9	3.3
MAXIMUM	22.7	19.9	3.9
MINIMUM	19.4	15.7	2.6
RANGE	3.3	4.2	1.3

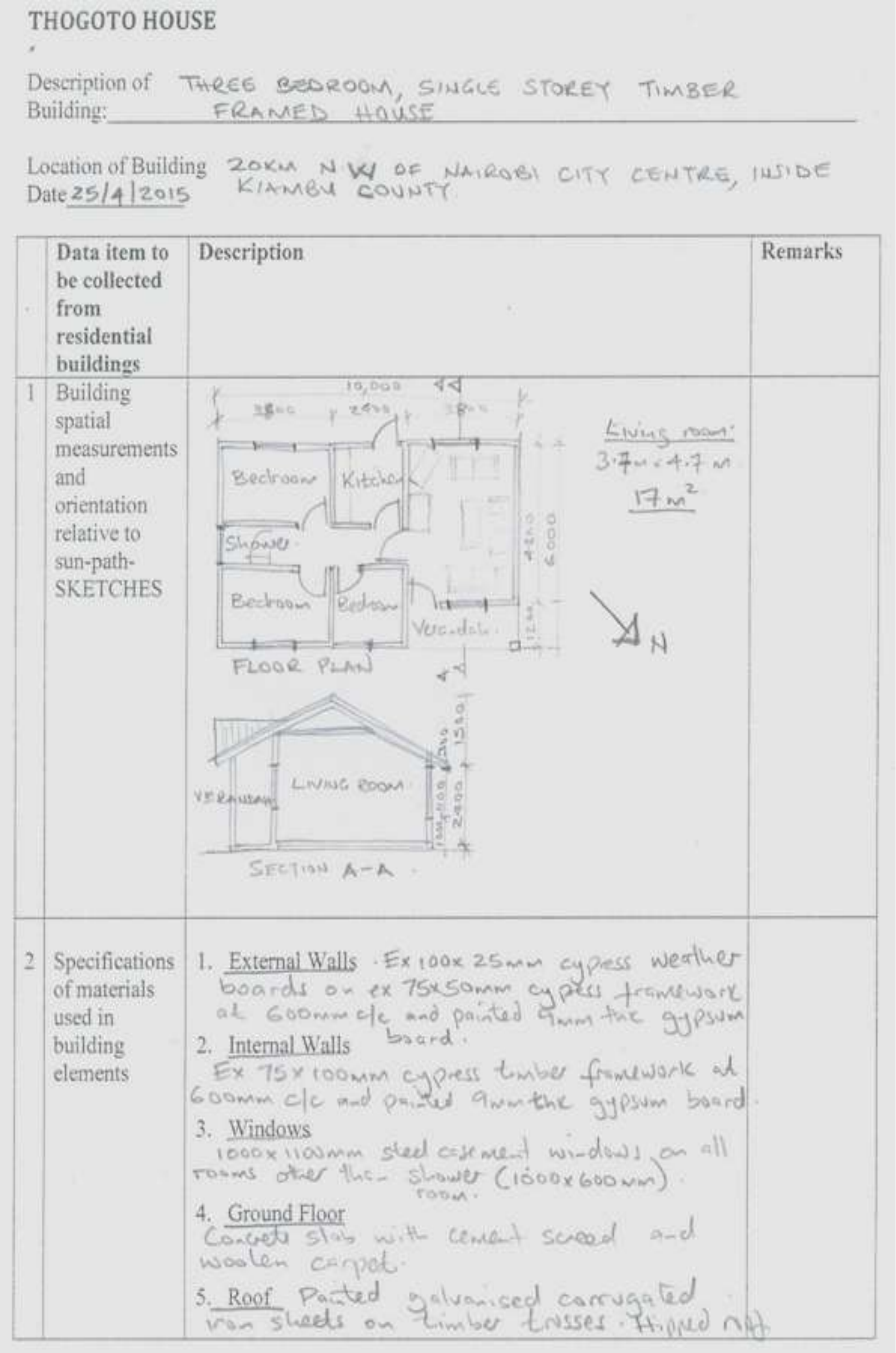
Appendix 4; Mean Daily temperature for month of May: Syokimau House

SYOKIMAU HOUSE			
	Measured Mean Daily Temperature		
Date in May	Measured Indoor	Measured outdoor	Range
1	22.1	18.5	3.6
2	21.5	17.9	3.6
3	21.8	18.6	3.2
4	21.1	17.0	4.1
5	22.1	18.6	3.5
6	21.9	18.2	3.7
7	22.4	18.3	4.1
8	21.6	18.1	3.5
9	22.7	18.9	3.8
10	22.3	18.4	3.9
11	22.4	18.7	3.8
12	22.4	18.9	3.5
13	22.9	19.3	3.6
14	23.6	20.0	3.6
15	23.1	19.4	3.8
16	22.7	18.9	3.7
17	22.8	18.5	4.3
18	22.5	18.6	4.0
19	22.3	18.2	4.1
20	22.1	18.4	3.7
21	22.6	18.3	4.3
22	22.0	18.1	4.0
23	21.7	17.5	4.2
24	21.7	17.8	3.9
25	21.7	17.4	4.3
26	22.5	18.1	4.4
27	21.5	18.0	3.5
28	21.5	17.3	4.2
29	20.8	16.8	4.0
30	20.2	16.2	4.0
31	21.0	17.1	3.9
MEAN	22.0	18.2	3.9
MAXIMUM	23.6	20.0	4.4
MINIMUM	20.2	16.2	3.2
RANGE	3.4	3.8	1.2

Appendix 5: Mean Daily temperature for month of May: Dandora House

DANDORA HOUSE			
Date in May	**Measured Mean Daily Temperature**		
	Measured Indoor	**Measured outdoor**	**Range**
1	21.0	18.4	2.5
2	20.1	17.7	2.4
3	20.9	18.6	2.3
4	19.3	16.8	2.4
5	20.7	18.6	2.1
6	20.3	18.1	2.2
7	21.1	18.2	2.8
8	20.0	18.0	2.0
9	21.6	18.9	2.6
10	21.0	18.3	2.6
11	21.2	18.6	2.5
12	21.1	19.0	2.1
13	21.7	19.3	2.4
14	22.7	20.1	2.6
15	22.0	19.4	2.6
16	21.4	18.9	2.5
17	21.6	18.4	3.2
18	21.2	18.5	2.7
19	21.0	17.9	3.0
20	20.7	18.4	2.3
21	21.3	18.2	3.1
22	20.6	18.0	2.6
23	20.1	17.4	2.7
24	20.1	17.6	2.4
25	20.1	17.2	2.9
26	21.2	18.1	3.2
27	19.9	17.9	2.0
28	19.8	17.0	2.7
29	18.9	16.6	2.3
30	18.0	15.9	2.2
31	19.2	16.9	2.3
MEAN	20.6	18.1	2.5
MAXIMUM	22.7	20.1	3.2
MINIMUM	18.0	15.9	2.0
RANGE	4.7	4.3	1.2

Appendix 6: Data collection sheet for field work: Thogoto House



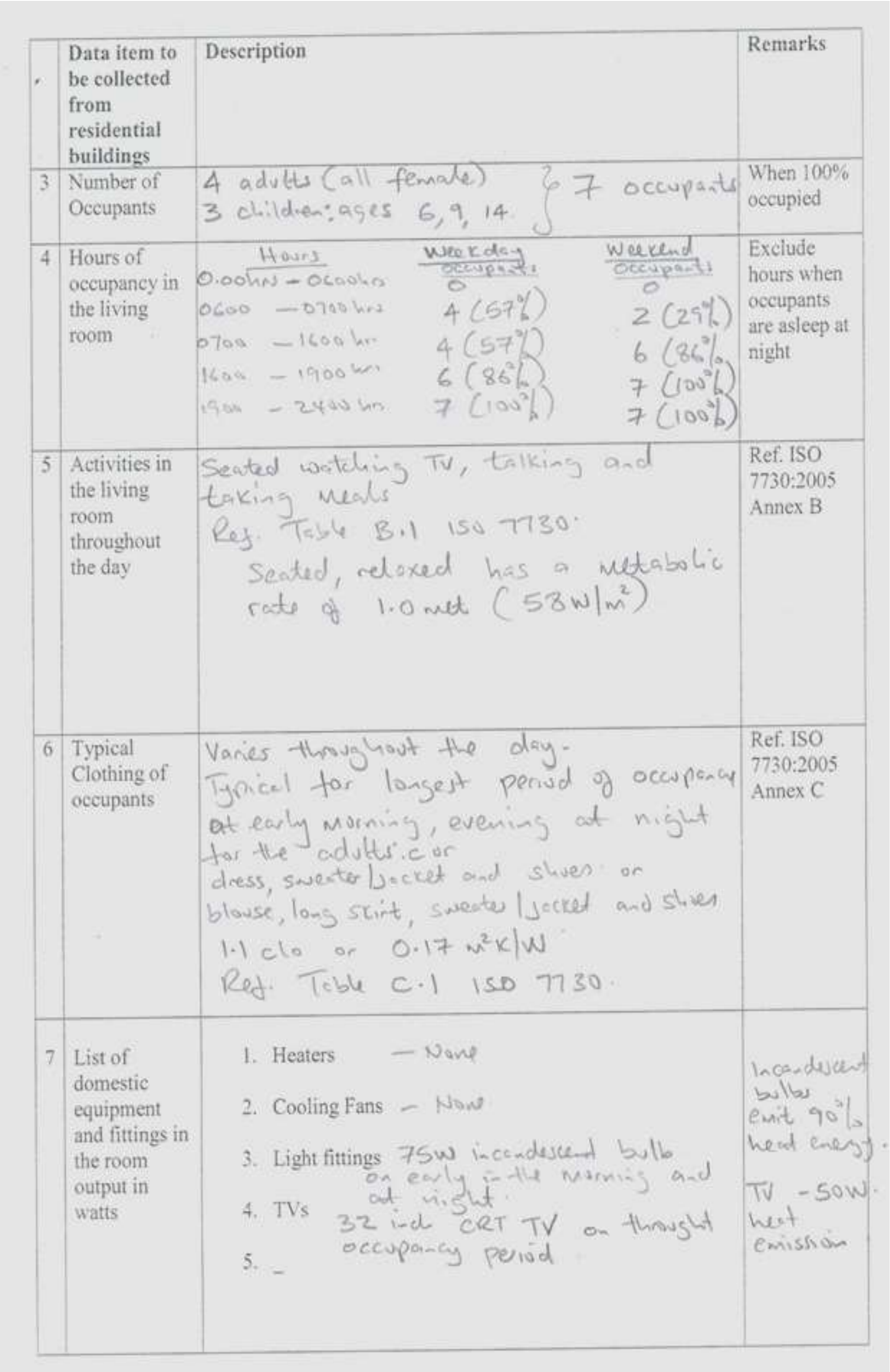
THOGOTO HOUSE

Description of Building: THREE BEDROOM, SINGLE STOREY TIMBER FRAMED HOUSE

Location of Building 20KM N W OF NAIROBI CITY CENTRE, INSIDE KIAMBU COUNTY

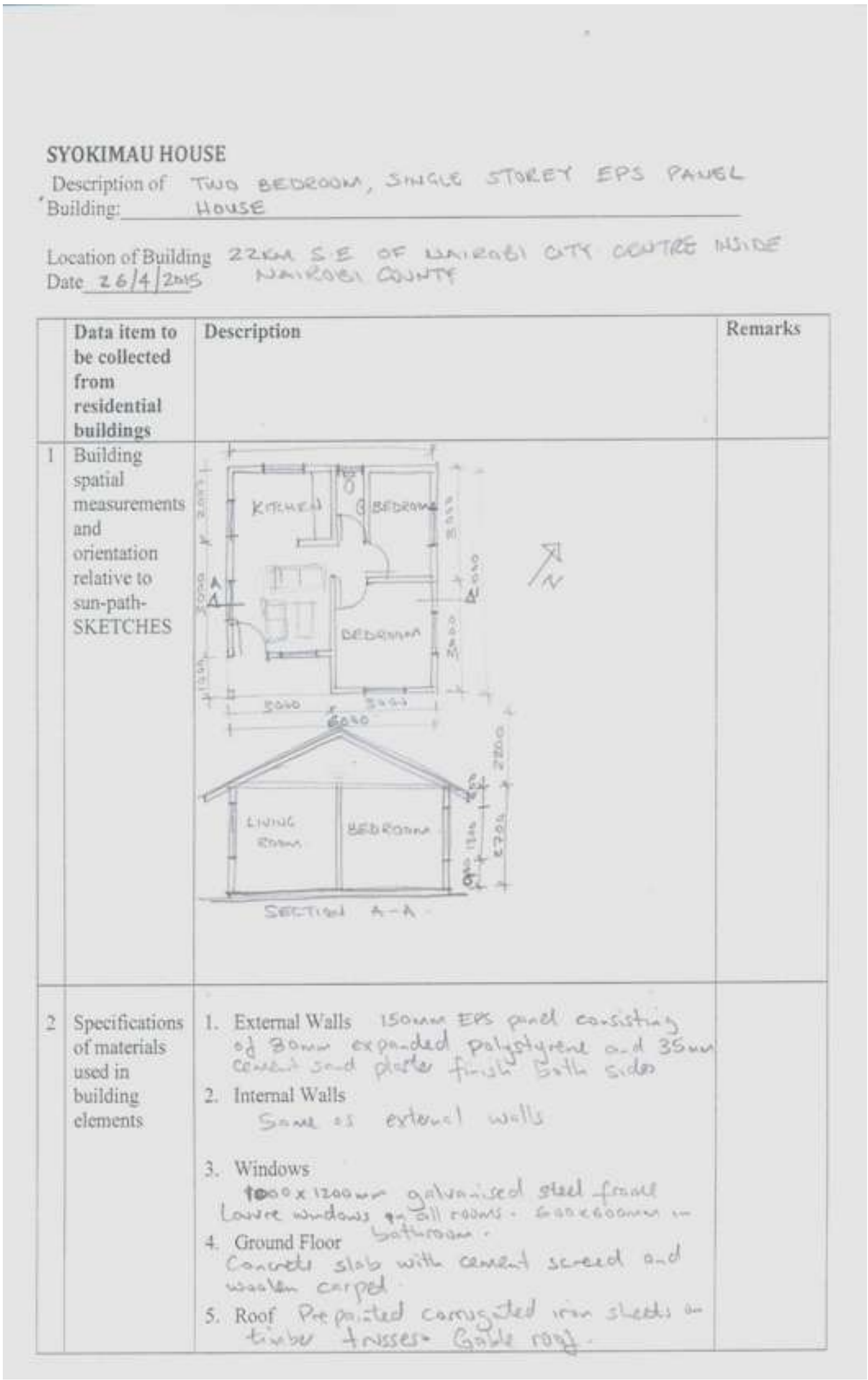
Date 25/4/2015

	Data item to be collected from residential buildings	Description	Remarks
1	Building spatial measurements and orientation relative to sun-path- SKETCHES	Living room: 3.7m x 4.7m 17m²	
2	Specifications of materials used in building elements	1. External Walls · Ex 100x 25mm cypess weather boards on ex 75x50mm cypess framework at 600mm c/c and painted 9mm thk gypsum board. 2. Internal Walls Ex 75x100mm cypress timber framework at 600mm c/c and painted 9mm thk gypsum board. 3. Windows 1000x1100mm steel casement windows on all rooms other than shower room (1000x600mm). 4. Ground Floor Concrete slab with cement screed and woolen carpet. 5. Roof Painted galvanised corrugated iron sheets on timber trusses. Hipped roof	



	Data item to be collected from residential buildings	Description	Remarks
3	Number of Occupants	4 adults (all female) 3 children: ages 6, 9, 14 } 7 occupants	When 100% occupied
4	Hours of occupancy in the living room	Hours — Weekday occupants — Weekend occupants 0.00hrs – 0600hrs — 0 — 0 0600 – 0700 hrs — 4 (57%) — 2 (29%) 0700 – 1600 hrs — 4 (57%) — 6 (86%) 1600 – 1900 hrs — 6 (86%) — 7 (100%) 1900 – 2400 hrs — 7 (100%) — 7 (100%)	Exclude hours when occupants are asleep at night
5	Activities in the living room throughout the day	Seated watching TV, talking and taking meals Ref. Table B.1 ISO 7730. Seated, relaxed has a metabolic rate of 1.0 met (58W/m²)	Ref. ISO 7730:2005 Annex B
6	Typical Clothing of occupants	Varies throughout the day. Typical for longest period of occupancy at early morning, evening at night for the adults: or dress, sweater/jacket and shoes or blouse, long skirt, sweater/jacket and shoes 1.1 clo or 0.17 m²K/W Ref. Table C.1 ISO 7730.	Ref. ISO 7730:2005 Annex C
7	List of domestic equipment and fittings in the room output in watts	1. Heaters — None 2. Cooling Fans – None 3. Light fittings 75W incandescent bulb on early in the morning and at night. 4. TVs 32 inch CRT TV on throught occupancy period 5. –	Incandescent bulbs emit 90% heat energy. TV – 50W. heat emission

Appendix 7: Data collection sheet for field work: Syokimau House



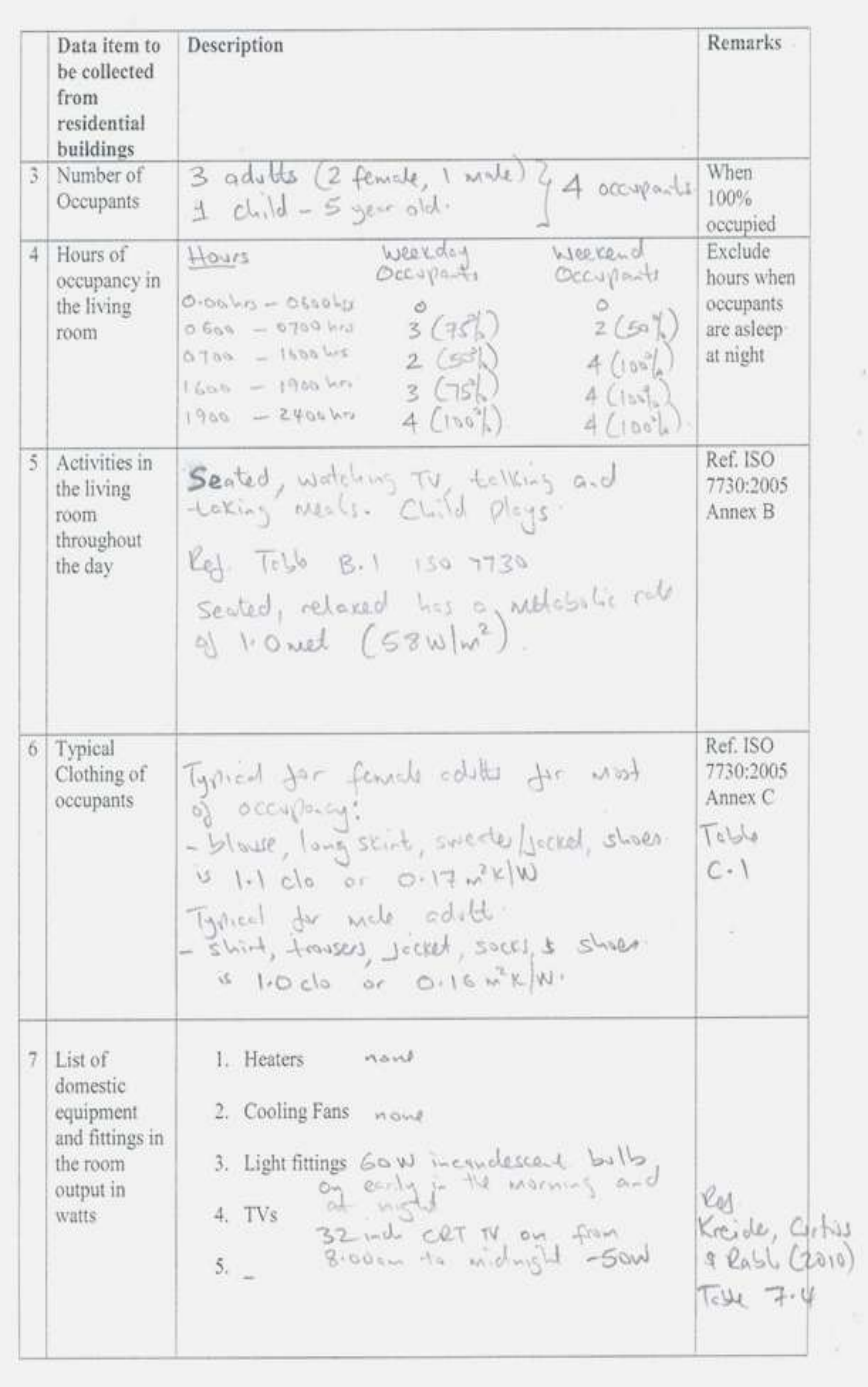
SYOKIMAU HOUSE

Description of Building: TWO BEDROOM, SINGLE STOREY EPS PANEL HOUSE

Location of Building 22KM S.E OF NAIROBI CITY CENTRE INSIDE NAIROBI COUNTY

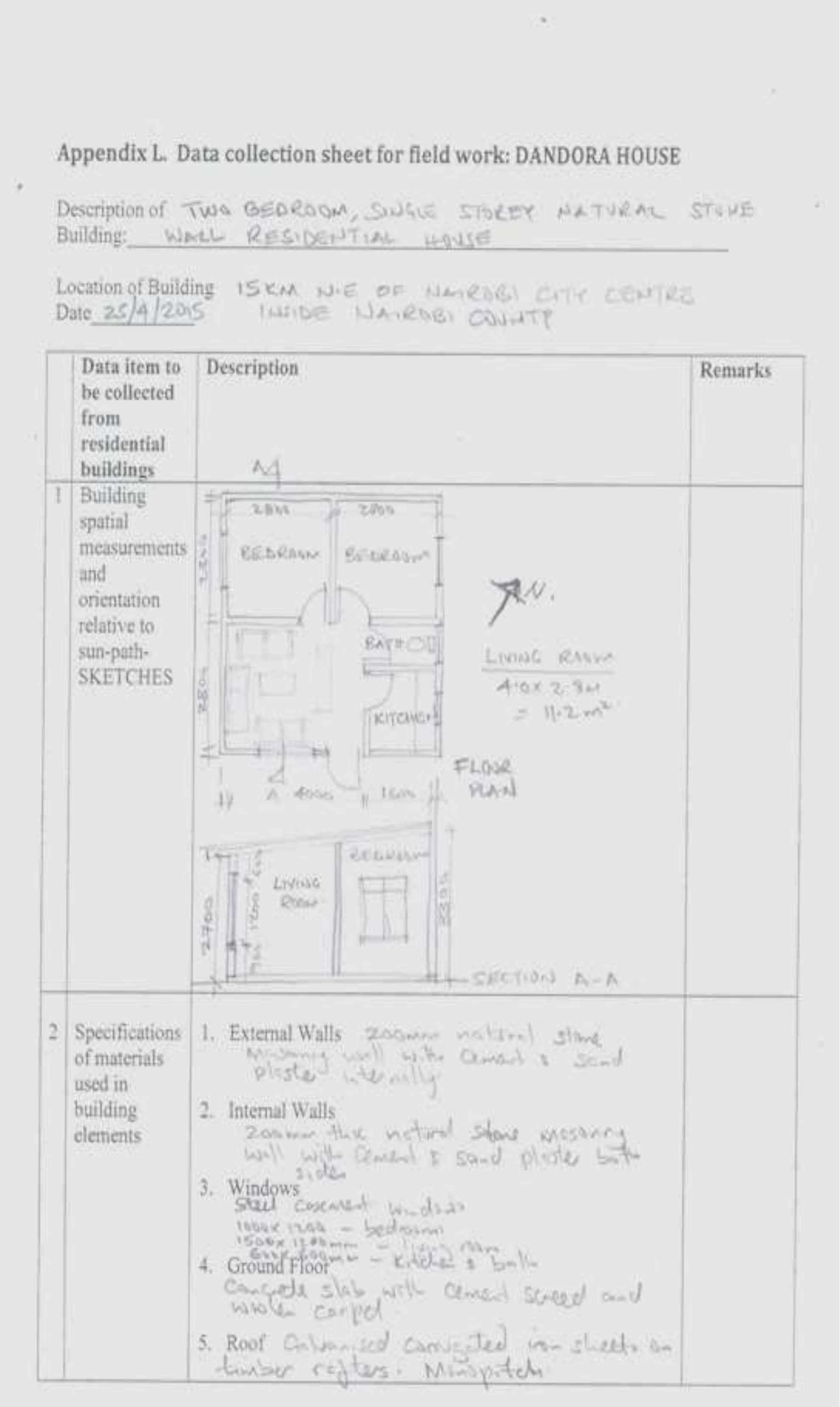
Date 26/4/2015

	Data item to be collected from residential buildings	Description	Remarks
1	Building spatial measurements and orientation relative to sun-path- SKETCHES	SECTION A-A	
2	Specifications of materials used in building elements	1. External Walls 150mm EPS panel consisting of 30mm expanded polystyrene and 35mm cement sand plaster finish both sides 2. Internal Walls Same as external walls 3. Windows 1000 x 1200mm galvanised steel frame Louvre windows in all rooms. 600x600mm in bathroom. 4. Ground Floor Concrete slab with cement screed and woolen carpet. 5. Roof Pre painted corrugated iron sheets on timber trusses. Gable roof.	



	Data item to be collected from residential buildings	Description	Remarks
3	Number of Occupants	3 adults (2 female, 1 male) 1 child – 5 year old. } 4 occupants	When 100% occupied
4	Hours of occupancy in the living room	Hours — Weekday Occupants — Weekend Occupants 0.00hrs – 0600hrs — 0 — 0 0600 – 0700 hrs — 3 (75%) — 2 (50%) 0700 – 1600 hrs — 2 (50%) — 4 (100%) 1600 – 1900 hrs — 3 (75%) — 4 (100%) 1900 – 2400 hrs — 4 (100%) — 4 (100%)	Exclude hours when occupants are asleep at night
5	Activities in the living room throughout the day	Seated, watching TV, talking and taking meals. Child plays Ref. Table B.1 ISO 7730 Seated, relaxed has a metabolic rate of 1.0 met (58W/m²).	Ref. ISO 7730:2005 Annex B
6	Typical Clothing of occupants	Typical for female adults for most of occupancy: - blouse, long skirt, sweater/jacket, shoes is 1.1 clo or 0.17 m²K/W Typical for male adult - shirt, trousers, jacket, socks & shoes is 1.0 clo or 0.16 m²K/W.	Ref. ISO 7730:2005 Annex C Table C.1
7	List of domestic equipment and fittings in the room output in watts	1. Heaters none 2. Cooling Fans none 3. Light fittings 60W incandescent bulb, on early in the morning and at night 4. TVs 32 inch CRT TV on from 8:00am to midnight –50W 5. –	Ref Kreider, Curtiss & Rabl (2010) Table 7.4

Appendix 8: Data collection sheet for field **work**: Dandora House

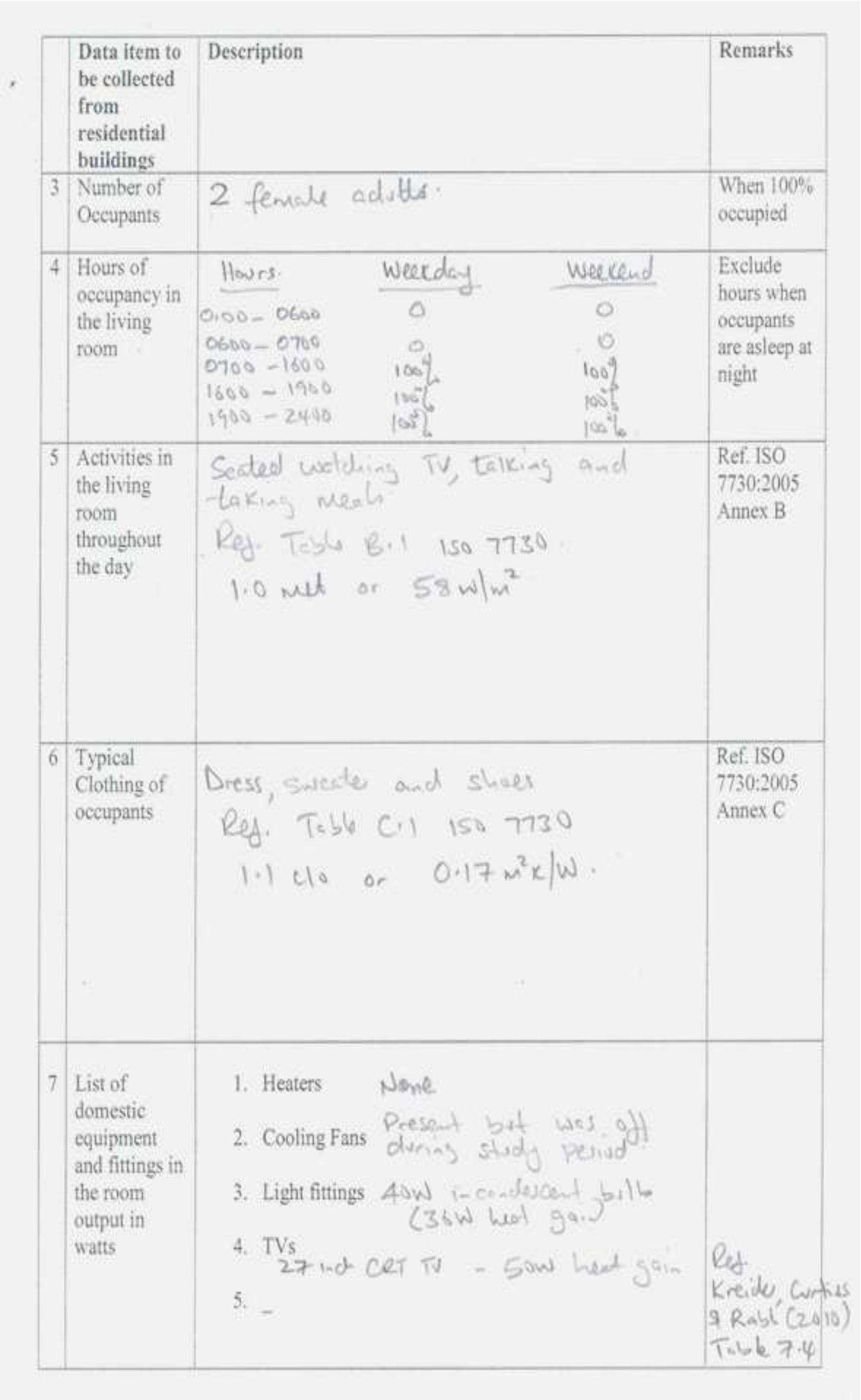


Appendix L. Data collection sheet for field work: DANDORA HOUSE

Description of Building: TWO BEDROOM, SINGLE STOREY NATURAL STONE WALL RESIDENTIAL HOUSE

Location of Building 15KM N.E OF NAIROBI CITY CENTRE INSIDE NAIROBI COUNTY
Date 25/4/2015

	Data item to be collected from residential buildings	Description	Remarks
1	Building spatial measurements and orientation relative to sun-path-SKETCHES	A 2800 2800 BEDROOM BEDROOM BATH KITCHEN N. LIVING ROOM 4.0 x 2.8M = 11.2m² FLOOR PLAN A 4000 1600 BEDROOM LIVING ROOM 2700 SECTION A-A	
2	Specifications of materials used in building elements	1. External Walls 200mm natural stone masonry wall with Cement & sand plaster internally 2. Internal Walls 200mm thick natural stone masonry wall with Cement & sand plaster both sides 3. Windows Steel casement windows 1000x 1200 – bedroom 1500x 1200mm – living room 600x 600mm – kitchen & bath 4. Ground Floor Concrete slab with Cement screed and woolen carpet 5. Roof Galvanised corrugated iron sheets on timber rafters. Mono pitch	



	Data item to be collected from residential buildings	Description	Remarks
3	Number of Occupants	2 female adults.	When 100% occupied
4	Hours of occupancy in the living room	Hours. — Weekday — Weekend 0100 – 0600 — 0 — 0 0600 – 0700 — 0 — 0 0700 – 1600 — 100% — 100% 1600 – 1900 — 100% — 100% 1900 – 2400 — 100% — 100%	Exclude hours when occupants are asleep at night
5	Activities in the living room throughout the day	Seated watching TV, talking and taking meals Ref. Table B.1 ISO 7730. 1.0 met or $58 W/m^2$	Ref. ISO 7730:2005 Annex B
6	Typical Clothing of occupants	Dress, sweater and shoes Ref. Table C.1 ISO 7730 1.1 clo or $0.17 m^2K/W$.	Ref. ISO 7730:2005 Annex C
7	List of domestic equipment and fittings in the room output in watts	1. Heaters None 2. Cooling Fans Present but was off during study period! 3. Light fittings 40W incandescent bulb (36W heat gain) 4. TVs 27 inch CRT TV – 50W heat gain 5. –	Ref. Kreider, Curtiss & Rabl (2010) Table 7.4

Appendix 9: Reference annexes from ISO 7730:2007

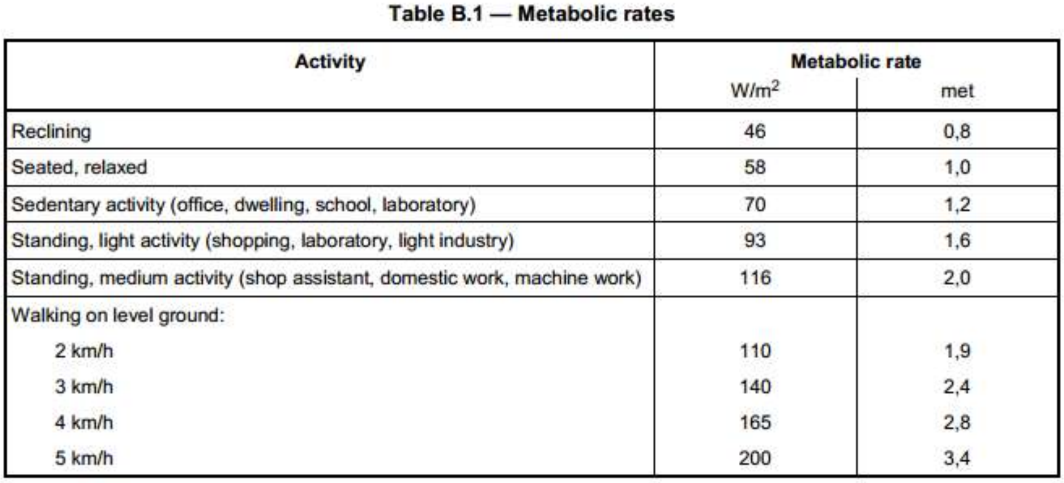


Table B.1 — Metabolic rates

Activity	Metabolic rate	
	W/m^2	met
Reclining	46	0,8
Seated, relaxed	58	1,0
Sedentary activity (office, dwelling, school, laboratory)	70	1,2
Standing, light activity (shopping, laboratory, light industry)	93	1,6
Standing, medium activity (shop assistant, domestic work, machine work)	116	2,0
Walking on level ground:		
2 km/h	110	1,9
3 km/h	140	2,4
4 km/h	165	2,8
5 km/h	200	3,4

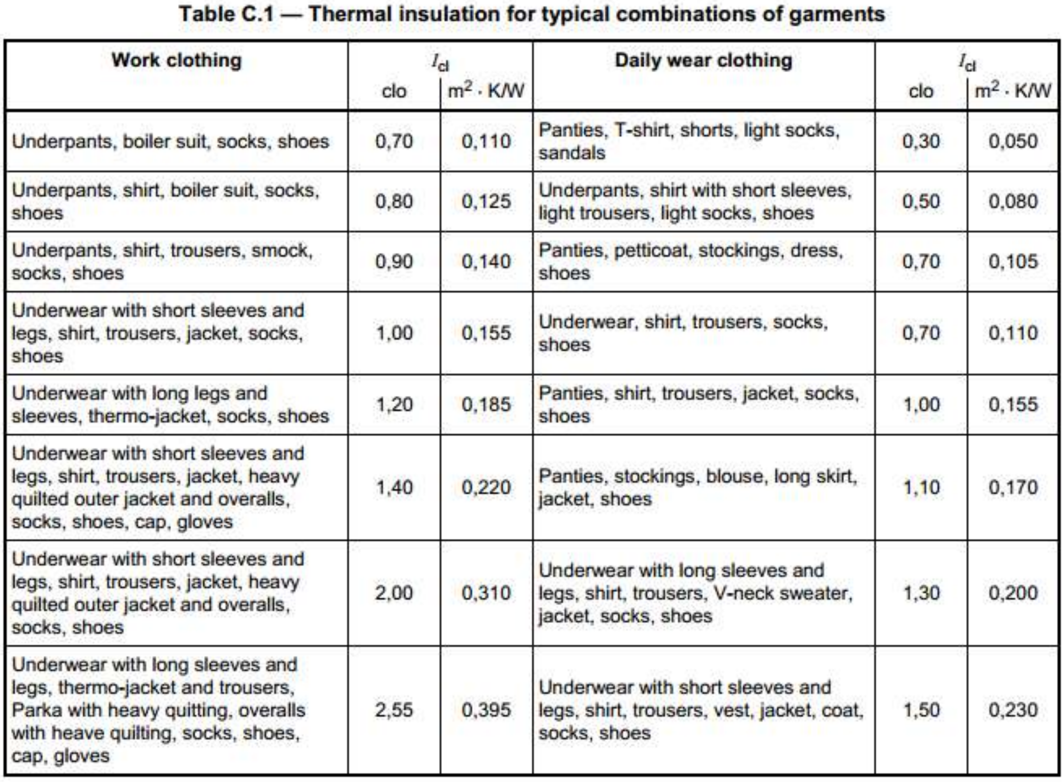


Table C.1 — Thermal insulation for typical combinations of garments

Work clothing	I_{cl}		Daily wear clothing	I_{cl}	
	clo	m^2 · K/W		clo	m^2 · K/W
Underpants, boiler suit, socks, shoes	0,70	0,110	Panties, T-shirt, shorts, light socks, sandals	0,30	0,050
Underpants, shirt, boiler suit, socks, shoes	0,80	0,125	Underpants, shirt with short sleeves, light trousers, light socks, shoes	0,50	0,080
Underpants, shirt, trousers, smock, socks, shoes	0,90	0,140	Panties, petticoat, stockings, dress, shoes	0,70	0,105
Underwear with short sleeves and legs, shirt, trousers, jacket, socks, shoes	1,00	0,155	Underwear, shirt, trousers, socks, shoes	0,70	0,110
Underwear with long legs and sleeves, thermo-jacket, socks, shoes	1,20	0,185	Panties, shirt, trousers, jacket, socks, shoes	1,00	0,155
Underwear with short sleeves and legs, shirt, trousers, jacket, heavy quilted outer jacket and overalls, socks, shoes, cap, gloves	1,40	0,220	Panties, stockings, blouse, long skirt, jacket, shoes	1,10	0,170
Underwear with short sleeves and legs, shirt, trousers, jacket, heavy quilted outer jacket and overalls, socks, shoes	2,00	0,310	Underwear with long sleeves and legs, shirt, trousers, V-neck sweater, jacket, socks, shoes	1,30	0,200
Underwear with long sleeves and legs, thermo-jacket and trousers, Parka with heavy quitting, overalls with heave quilting, socks, shoes, cap, gloves	2,55	0,395	Underwear with short sleeves and legs, shirt, trousers, vest, jacket, coat, socks, shoes	1,50	0,230

Appendix 10: Simulated monthly load of discomfort in Thogoto House

MONTH	MONTHLY DEGREE HOURS OF DISCOMFORT					
	200mm Stone wall Plaster inside only	200mm Stone wall Plaster inside and outside	GCI sheets with timber frame	GCI sheets with timber frame gypsum board lining	200 mm concrete blocks	200 mm fired clay bricks
Jan	0	0	2	0	0	0
Feb	0	0	2	0	0	0
Mar	0	0	2	0	0	0
Apr	0	0	0	0	0	0
May	0	0	16	1	0	0
Jun	71	65	184	33	42	9
Jul	367	354	714	241	298	163
Aug	213	202	482	133	161	81
Sep	89	85	206	62	71	40
Oct	1	1	28	1	0	0
Nov	2	1	34	1	0	0
Dec	6	5	64	4	2	0
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TOTAL	749.6	713.4	1734	474.9	575.3	292.4

MONTH	MONTHLY DEGREE HOURS OF DISCOMFORT					
	300mm thick rammed earth	400mm thick rammed earth	Timber frame and gypsum board lining	Timber boards on timber frame	150mm single EPS panel	240mm double EPS panel
Jan	0	0	0	0	0	0
Feb	0	0	0	0	0	0
Mar	0	0	0	0	0	0
Apr	0	0	0	0	0	0
May	0	0	0	1	0	0
Jun	2	1	7	35	0	0
Jul	111	59	91	218	0	0
Aug	43	17	44	137	0	0
Sep	25	11	23	60	0	0
Oct	0	0	0	3	0	0
Nov	0	0	0	2	0	0
Dec	0	0	0	6	0	0
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TOTAL	180	87.9	164.4	461.6	0.1	0.1

Appendix 11: Simulated monthly load of discomfort in Syokimau House

MONTH	MONTHLY DEGREE HOURS OF DISCOMFORT					
	200mm Stone wall Plaster inside only	200mm Stone wall Plaster inside and outside	GCI sheets with timber frame	GCI sheets with timber frame gypsum board lining	200 mm concrete blocks	200 mm fired clay bricks
Jan	0	0	4	0	0	0
Feb	0	0	2	0	0	0
Mar	0	0	6	0	0	0
Apr	0	0	0	0	0	0
May	2	1	24	2	1	0
Jun	120	114	260	81	127	72
Jul	474	465	812	368	496	364
Aug	275	267	514	219	283	200
Sep	101	99	172	86	104	75
Oct	1	1	12	1	1	0
Nov	2	2	8	5	2	0
Dec	5	5	12	8	5	1
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TOTAL	979	953.1	1826	769.4	1018.3	713.1

MONTH	MONTHLY DEGREE HOURS OF DISCOMFORT					
	300mm thick rammed earth	400mm thick rammed earth	Timber frame and gypsum board lining	Timber boards on timber frame	150mm single EPS panel	240mm double EPS panel
Jan	0	0	0	0	0	0
Feb	0	0	0	0	0	0
Mar	0	0	0	0	0	0
Apr	0	0	0	0	0	0
May	0	0	1	3	0	0
Jun	55	41	41	76	1	2
Jul	351	316	233	320	104	96
Aug	181	163	137	195	40	37
Sep	75	69	53	66	18	16
Oct	0	0	1	2	0	0
Nov	0	0	2	2	0	0
Dec	0	0	3	3	0	0
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TOTAL	661.5	590.2	470.8	666.7	162.3	150.5

Appendix 12: Simulated monthly load of discomfort in Dandora House

MONTH	MONTHLY DEGREE HOURS OF DISCOMFORT					
	200mm Stone wall Plaster inside only	200mm Stone wall Plaster inside and outside	GCI sheets with timber frame	GCI sheets with timber frame gypsum board lining	200 mm concrete blocks	200 mm fired clay bricks
Jan	0	0	0	0	0	0
Feb	0	0	0	0	0	0
Mar	0	0	0	0	0	0
Apr	0	0	0	0	0	0
May	0	0	14	2	0	0
Jun	84	74	211	44	56	14
Jul	471	449	768	279	413	268
Aug	246	230	448	140	204	115
Sep	105	100	234	55	92	54
Oct	1	0	24	2	0	0
Nov	3	2	82	4	1	0
Dec	6	4	116	6	3	0
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TOTAL	916.2	860	1897.2	532.3	769.2	451.1

MONTH	MONTHLY DEGREE HOURS OF DISCOMFORT					
	300mm thick rammed earth	400mm thick rammed earth	Timber frame and gypsum board lining	Timber boards on timber frame	150mm single EPS panel	240mm double EPS panel
Jan	0	0	0	0	0	0
Feb	0	0	0	0	0	0
Mar	0	0	0	0	5	9
Apr	0	0	0	0	0	0
May	0	0	0	0	0	0
Jun	6	1	9	34	0	0
Jul	221	149	111	283	0	0
Aug	79	46	48	144	0	0
Sep	42	24	18	57	0	0
Oct	0	0	0	1	0	0
Nov	0	0	0	2	0	0
Dec	0	0	1	4	0	0
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TOTAL	348.5	219.9	186.2	528	5.1	9.5