Determination of the Thermo-physical Properties of Walling Materials for Thermal Comfort in the Sub-Tropic Highland Climate, Kenya

R. N. Kariuki, B. N. Mugwima and J. W. Kaluli

Abstract—People in modern society spend about 90% of their time indoors. The requirement of sustainable (or green) building includes the necessity to create healthy and comfortable indoors such as satisfaction with the thermal environment. The thermo-physical properties of materials used in construction of the building envelop, such as the walls, will affect this indoor thermal environment depending on the external weather conditions. Nairobi’s outdoor temperatures of 10°C to 26°C mostly fall out of the optimal range of 20°C to 23°C that will minimize the need for indoor temperature adjustment. Yet in Kenya the applicable regulation regarding walls in buildings does not set any requirement regarding thermal performance. The international trend is to specify the thermo-physical properties (usually the thermal transmittance (U-value), and thermal mass) in the regulation of the building elements. There is therefore need for development of a design criterion for specifying building materials for thermal performance to guide architects and engineers in material specifications. This paper is a review of existing literature on the relationship between thermal comfort and building materials. It forms a background for studies to collect data that will form a basis for regulation and assessment of the suitability of building materials developed in or imported into Kenya.

Keywords— Walling, thermal comfort, sub-topic climate, thermal transmittance, thermal mass.

I. INTRODUCTION

Buildings accommodate people, provide security, privacy and protect them from the weather elements. In modern society people spend about 90% of their time indoors [1]. The requirement of sustainable (or green) building includes the necessity to create healthy and comfortable indoors including satisfaction with the thermal environment [2]. That condition of mind, which expresses satisfaction with the thermal environment, is the thermal comfort [3].

The thermo-physical properties of materials used in construction of the building envelop, such as the walls, will affect the indoor thermal comfort. Heat, from solar radiation, flows by conduction through various building elements such as walls, roof and floors as well as by convection and radiation at the surfaces. Part of the heat energy is stored in the building fabric.

In selecting building materials designers have a wide range to choose from in order to, among other requirements, achieve thermal comfort in buildings. The main properties of the construction elements that determine the rate of the heat exchange are thermal transmittance (U-value) and thermal mass. Materials may be lightweight with low thermal transmittance for insulation or dense with high thermal mass for collecting, storing solar heat and releasing it when needed especially at night.

In Nairobi, Kenya, where the mean temperatures range from 10oC to 26oC, the most common materials used for walls have very different thermal properties. Natural stone and earth which account for about 57% of materials for walls have high U-values and high thermal mass while galvanized iron sheets which account for about 27% have high U-values and low thermal mass. On the other hand prefabricated insulated walling panels which are being introduced into the country have low U-values and low thermal mass. Studies on residential buildings in Yemen, Turkey, Chile and Kenya [4-7] suggest that walls of high thermal mass using local materials are better at moderating diurnal temperature variations compared to those of more modern low thermal mass and insulating materials.

The relationship between thermal properties of building materials and thermal comfort forms a basis for building regulations. The regulations in the United Kingdom and Japan specify maximum thermal U-values for walls [8]. In South Africa, the standards incorporate both the thermal capacity and thermal transmittance of materials for walling [9]. In Kenya, building materials for design and construction of building walls are regulated by the Local Government (Adoptive By-Laws) Building Order (1968) and specify minimum thicknesses of selected materials for structural stability and not for indoor thermal environment.

The international trend is to specify the thermo-physical properties (usually the thermal transmittance (U-value), and thermal mass in the regulation) of the building elements. There
is therefore need for development of a design criterion for specifying building materials for thermal performance to guide architects and engineers in material specifications. This paper is a review of existing literature on the relationship between thermal comfort and building materials. It forms a background for studies to collect data that will form a basis for regulations and assessment of the suitability of building materials developed in or imported into Kenya.

II. BUILDING FOR THERMAL COMFORT

Thermal comfort is defined as "that condition of mind which expresses satisfaction with the thermal environment" [3], and is dependent on environmental variables: air temperature, mean radiant temperature, humidity, air velocity and personal variables such as clothing and metabolic rate. 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. Temperatures outside comfort range have been associated with respiratory diseases [10], emotional stress and low productivity [11] and mortality [12].

A necessary condition for thermal comfort is a balance between the metabolic heat production and the heat loss from the body to the environment. 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 [13].

The environmental factors for thermal comfort may be achieved by passive design through the implementation of features in buildings to work with natural processes rather than by artificial heating and ventilation [14]. This involves the selection of construction materials with appropriate thermal properties. Passively designed buildings are naturally conditioned and run with a minimum of energy input for thermal comfort. Energy efficiency is an important feature in making a building material environmentally sustainable. The goal of using energy-efficient materials is to reduce the cost of air conditioning and hence reduce the long-term energy costs of operating a building. A rammed earth house constructed for passive heating and cooling was found to result in an energy saving of 50% compared to that of other conventional houses in Southern Australia [15].

The energy performance in buildings may be modelled using mechanistic (white box), black box or grey box models. Mechanistic models are developed based on "white box" or physical methods which employ heat transfer equations based on detailed description of the building geometry and thermal properties. “Black box” models use mainly statistical data collected over an exhaustive period of time. The “grey box” model is a hybrid of the white box and black box and uses basic prior knowledge of the building characteristics combined with a reasonable amount of measured data to estimate the missing physical parameters to describe the building thermal performance. Based on the “white box” model, it is possible to use computer simulation programs like Energy Plus, TRNSYS, and Fluent which have been developed to predict the indoor thermal environment and energy requirement. The input data for such programs is the building geometric data, climatic data and the building material properties [16].

III. THERMAL COMFORT IN THE SUBTROPIC HIGHLAND KENYA

In naturally conditioned buildings it has been found that the temperature which occupants will find acceptable is linearly related to the monthly mean of the outdoor temperature. Humphreys and Nicol developed a formula for predicting comfortable temperatures [17] by examining outdoor mean temperatures:

\[ T_c = 13.5 + 0.54T_o \]  (1)

Where \( T_c \) is the comfortable indoor temperature and \( T_o \) is the monthly mean outdoor air temperature. This is the basis for the ASHRAE Standard 55 [18] where the comfort zone is \( T_c \pm 3.5^\circ C \) for 80% acceptability limits.

For Nairobi, Kenya, in the sub-tropic highland climatic zone, the mean monthly temperature ranges from 15.5°C to 19.0°C. In May, for example, the mean monthly temperature is 18°C and therefore the expected comfortable indoor temperature is between 17.0°C and 26.7°C. The lower mean values of temperature (Mean Minimum of 13°C in May) suggest that it is necessary to raise indoor temperatures for a significant period of the day in Nairobi to achieve thermal comfort (Fig. 1).

Fig. 1 Range of Comfortable Indoor Temperature for Nairobi from 1951 to 2010. The upper limit of comfortable temperature is 30°C, and the lower limit is 13°C. Monthly mean of the maximum and minimum temperature are also shown. The monthly mean indoor temperature is within 

\[ T_c \pm 3.5^\circ C \] for 80% acceptability limits.

IV. THERMO-PHYSICAL BEHAVIOR OF BUILDING MATERIALS

The primary parameters that determine heat transfer of a material are its density, specific heat capacity, and thermal conductivity. Thermal conductivity is the property of a material to conduct heat by transfer of internal energy through microscopic diffusion and collisions of particles (molecules, electrons and atoms) within a body. Fourier’s Law of Heat
Conduction states that the time 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. The specific heat capacity is the amount of heat per unit mass required to raise the temperature of the material by one degree, a measure of ability to store heat energy in the form of vibrations of atoms of the material [19].

In building elements, thermal transmittance (or U-value) is used to measure the rate of transfer of heat through one square metre of a structure divided by the difference in temperature across the structure expressed in W/m²K. U-value takes into account heat transfer due to thermal conduction, thermal radiation and thermal convection. For a building element like the wall, the U value of the element is calculated as follows:

\[ U = 1/ (R_{so} + R_{si} + R_1 + R_2 + \ldots) \]  

(2)

Where

- Rso is the fixed external resistance; Rsi is the fixed internal resistance and R1+R2… is the sum of all the resistances of the building materials in the constructional element.

Thermal mass in J/m²K measures the amount of heat stored in the building fabric which is later released to control temperature fluctuations. It takes into account specific heat capacity, density and thickness of the material layers forming the element. For a building element like the wall, the thermal mass of the element K is calculated as follows:

\[ K = c_1.\rho_1.d_1 + c_2.\rho_2.d_2 + c_3.\rho_3.d_3 + \ldots \]  

(3)

where:

- c is specific heat capacity of layer (J/kg K), ρ is density of layer (kg/m³) and d is the thickness of layer (m)

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. In this regard, two types of materials are identified: thermal insulators with low thermal transmittance and thermal mass which store incoming energy and later release this energy as heat [20].

The heat transfer processes of convection, conduction, radiation, heat storage and release results in a complex relationship between the outdoor and indoor temperatures in naturally ventilated buildings. As the outdoor air temperature and solar radiation intensity change significantly during day and night, the indoor air temperature also varies with time. 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. 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 [21].

Recent studies of thermal performance of the different walling materials around the world seem to suggest better performance by materials of high thermal mass. In hot dry Sanaa, Yemen [4] demonstrated that indigenous building materials in Yemen (mud brick and fired bricks) perform better than contemporary materials (stone and concrete) in reducing temperature fluctuations within buildings in the critical very cold temperatures between November and March. In warm dry-summer continental climate in Yozgat, Turkey [5] suggests 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. Palme, Guerra & Alfaro in San Pedro De Atacama, Chile concluded that earth construction performed better than concrete blocks and timber in guaranteeing internal thermal stability and comfort [6]. However, other workers have found insignificant differences in performance of mud bricks, insulated panels and fired clay brick in humid subtropical climate of Sydney, Australia.

V. THERMO-PHYSICAL PROPERTIES OF WALLING MATERIALS IN NAIROBI, KENYA

In Nairobi, Kenya a wide range of materials for walling are available. The most commonly used are stone (47.4%), galvanized corrugated sheets (26.9%), Bricks/blocks of concrete and clay (14.0%), mud (9.1%) and wood (1.9%) [22]. In addition, structural insulated prefabricated panels consisting of two outer layers of structural facing material of concrete or compressed fibres separated by an insulated core of polymer foam of polystyrene are being promoted in the country for energy saving and faster construction.

With all these materials having different thermal transmittance and thermal mass values (Table1) it is expected that they will result in different internal temperature values throughout a 24 hour period depending on the external thermal conditions.
A study in Nairobi in which closed test chambers were used to assess the effect of thermal mass of materials on indoor temperature concluded that high thermal capacity materials (stone wall with concrete roof tiles) were more effective in moderating extreme temperatures compared to timber wall with galvanized iron roofing sheets [7]. The study was limited in number of materials studied and could not take into account the effects of natural ventilation that occurs in actual buildings.

VI. BUILDING REGULATIONS FOR THERMAL PERFORMANCE

The requirement for thermal comfort and the relationship with properties of construction materials forms a basis for building thermal regulations in the different climatic zones around the world. These regulations reflect the nature of the climatic conditions with lower transmittance values for colder climates. In the United Kingdom the Building Regulations (2010) specifies maximum thermal transmittance values (U-values) of 0.25 W/m²K. 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/m²K to 0.53 W/m²K for walls [23].

In the United States, the International Energy Conservation Code 2004 [25] was devised by the International Code Council and sets rules for residential (with less than 4 floors) and for small and simple commercial buildings for eight climatic zones [24]. Unlike other cited regulations, the IECC distinguishes between light weight walls from massive walls in setting U-values. These values range from 0.32-0.47 W/m²K for wood frame walls and 0.32-1.12 W/m²K for massive walls. The South African National Standard for Energy Efficiency in Buildings [9] uses a CR-value which 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.

In Kenya, building materials for design and construction of building walling are regulated by the Local Government (Adoptive By-Laws) Building Order (1968) and specify in the Third Schedule the minimum thicknesses of only stone, concrete or fired clay blocks and bricks as 8 1/2"(216mm) for walls not exceeding 12 feet (3660mm) in height. This regulation is concerned with structural stability rather control of internal thermal conditions and is therefore inadequate to guide architects and engineers, regulate the building industry or assess suitability of materials regarding provision of comfortable indoor thermal environment in this country.

VII. CONCLUSIONS AND RECOMMENDATIONS

The thermal comfort standards suggest that for the outdoor temperature in Nairobi, indoor temperatures in buildings require adjustment for a healthy and comfortable environment. Passive design measures such as selection of building materials with appropriate thermal properties should enable an increase in indoor temperatures compared to outdoor temperatures in the colder hours of the day.

Given the range of local and imported materials available which have significant differences in thermo-physical properties, studies are required for determining which of these properties are desirable for this climatic zone. Such a study

### TABLE I

<table>
<thead>
<tr>
<th>Wall Type</th>
<th>U-Value (W/m²K)</th>
<th>Thermal Mass (J/m²K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 200 mm natural stone masonry plastered on one side</td>
<td>2.86</td>
<td>367,800</td>
</tr>
<tr>
<td>2 Galvanized corrugated iron sheets with ex 75 x 50mm frame</td>
<td>3.34</td>
<td>10,300</td>
</tr>
<tr>
<td>3 200 mm lightweight concrete blocks plastered on both sides</td>
<td>0.81</td>
<td>135,600</td>
</tr>
<tr>
<td>4 300mm thick rammed earth stabilized with cement and plastered on both sides</td>
<td>2.08</td>
<td>547,800</td>
</tr>
<tr>
<td>5 Timber frame with ex 25mm thick cypress, ex 75 x 50mm frame and 9mm gypsum board interior lining</td>
<td>1.66</td>
<td>22,700</td>
</tr>
<tr>
<td>6 150mm structural insulated panel consisting of 80 mm expanded polystyrene and 35mm plaster on both sides</td>
<td>0.34</td>
<td>93,800</td>
</tr>
<tr>
<td>7 150mm Fiber reinforced calcium silicon board with fiber and cement reinforced EPS</td>
<td>0.20</td>
<td>11700</td>
</tr>
</tbody>
</table>
will provide design criteria for the selection and specifications of materials by architects and engineers. The data collected may be used for development of building regulations, which are currently inadequate, regarding materials for thermal comfort. It will also determine the required thermo-physical properties of building materials to be imported into Kenya and to form a basis for research in materials that are appropriate locally for a comfortable, healthy and energy saving indoor environment.

REFERENCES