Cardiff University

The contribution of traditional building materials to hygrothermal comfort in Libyan domestic buildings

By

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ABSTRACT

Buildings in Libya and other parts of the world are often heavily dependent on mechanical heating, ventilation, and air conditioning (HVAC) systems to compensate for their poor hygrothermal performance. This results in higher energy consumption and increased greenhouse emissions associated with these systems. To reduce energy use, research into the use of passive systems that can reduce or even eliminate some of the energy demand on active systems has gained global momentum.

Representing the boundary between internal and external conditions, the building envelope design is a key factor affecting the building's energy performance and hygrothermal comfort. The materials used in the building envelope impact buildings' hygrothermal comfort and energy consumption by transferring, storing and releasing heat and moisture when the humidity and temperature conditions vary in the building. This research focuses on building materials' hygrothermal properties and how they can be used to provide hygrothermal comfort for occupants of Libyan houses.

The research used a methodology that combines energy and hygrothermal performance monitoring of Case Studies, laboratory-based categorisation of common Libyan building materials and hygrothermal simulations of building models.

A literature review showed that the building envelope's hygrothermal properties could improve indoor hygrothermal conditions by creating moisture and thermal buffering. The following materials representing Libya's traditional and modern building materials were selected for this research; Limestone, Hollow Concrete, Sandstone, Mud Block, Clay, and Camel's Hair.

There was a lack of data in the published research regarding the hygrothermal properties of some of the selected building materials in the context of Libya. To obtain the missing data, the following material properties were experimentally investigated; Moisture Buffer Value (MBV), Water Vapor Diffusion Resistance Factor (μ Value), Sorption Isotherm (u), Water Absorption Coefficient (Aw), Density (ρ), Thermal Conductivity (λ), Thermal Diffusivity (α), and Specific Heat Capacity (C_p). The Porosity test was not undertaken due to Covid.

The data from the hygrothermal monitoring of Case Studies was used to construct and calibrate three Case Study computer models in Design-Builder and WUFI Plus. Material testing data was used to design and construct new walls to study the impact of envelope materials choice on the hygrothermal performance of the Case Study models

The results of the hygrothermal categorisation showed that Limestone, Mud Block, Clay and Camel's hair have overall better hygrothermal properties than Hollow Concrete and Sandstone. The results also showed that some of the building materials from Libya are unique to their climatic and geographical context, and their hygrothermal properties can differ from published research findings from a different geo-climatic context.

The results of the hygrothermal simulation in Design-Builder and WUFI Plus showed that some of the materials could be used to improve hygrothermal conditions. It was found that the introduction of Camel's hair insulation helped improve hygrothermal comfort and reduce the energy consumption of the Case Study Houses.

Keywords; Hygrothermal comfort, Hygrothermal behaviour, Building envelope, Traditional materials, WUFI Plus, Design-Builder, Hygrothermal simulation, Building models calibration.

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List of Acronyms

ΔIP	*IPBC-IPBC1*
ΔOP	*OPBC-OPBC1*
1D	One Dimensional
2D	Two Dimensional
3D	Three Dimensional
Air-Temp °C	Air temperature
AMR	Automated energy meter readings
ASHRAE	The American Society of Heating, Refrigerating and Air-Conditioning Engineers
ASTM	American Society of Testing and Materials
BESTEST	Comparative Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs
BS	British standard
CR	Condensation risk
CV	Coefficient of the Variation
CV(RMSE)	Coefficient of the Variation of the Root Mean Square Error
DOE-2	Based Building Energy Use and Cost Analysis Software
DR	Dryness rate
EMC	Equilibrium moisture content
EN	European Standards
EVO	Efficiency Valuation Organization
FEMP	Federal Energy Management Program
Gen-Opt	Generic Optimization Program
HVAC	Heating Ventilation and Air Conditioning
IC	Influence Coefficient
In-RH%	Indoor relative humidity
IoT	internet of things
IPBC	Base Case input
IPBC1	Case 1 input
ISO	International Organization for Standardization
LIM	Lowest isopleth for mould
MBE	Mean Bias Error
MBV%	Moisture Buffering Value
MCv	Moisture Content mass by volume
MCw	Moisture Content mass by mass
MgCl2·6H2O	Magnesium Chloride Hexahydrate
NaBr	Sodium Bromide
NaCl	Sodium Chloride
NMBE	Normalized Mean Bias Error
Nordtest	Nordic organisation for cooperation within the area of testing
OPBC	Base Case output
OPBC1	Case1 output
Oper-Temp °C	Operative temperature
Out-RH%	Outdoor relative humidity
Out-Temp °C	Outdoor temperature
Rad-Temp °C	Radiant temperature
RH	Relative humidity
SD	Standard Deviation
TCM	Test Cell Model

TMC%	Total Moisture Content
TRNSYS	Transient System Simulation Tool
W1HC	Hollow Concrete 200 mm
W1LS	Limestone 200 mm
W1MB	Mud Block 200 mm
W1SS	Sandstone 200 mm
W2CH	Camel Hair+ Clay Plaster 350 mm
W2CL	Clay 300
W2HC	Hollow Concrete 300 mm
W2LS	Limestone 300 mm
W2MB	Mud Block 300 mm
W2SS	Sandstone 300 mm
W3HC	Hollow Concrete +Cement Plaster (250mm)
W3LS	Limestone +Cement Plaster (250mm)
W3MB	Mud Block +Cement Plaster (250mm)
W3SS	Sandstone +Cement Plaster (250mm)
W4HC	Hollow Concrete +Cement Plaster (350mm)
W4LS	Limestone +Cement Plaster (350mm)
W4MB	Mud Block +Cement Plaster (350mm)
W4SS	Sandstone +Cement Plaster (350mm)
W5HC	Hollow Concrete +Clay Plaster (250mm)
W5LS	Limestone +Clay Plaster (250mm)
W5MB	Mud Block +Clay Plaster (250mm)
W5SS	Sandstone +Clay Plaster (250mm)
W6HC	Hollow Concrete +Clay Plaster (350mm)
W6LS	Limestone +Clay Plaster (350mm)
W6MB	Mud Block +Clay Plaster (350mm)
W6SS	Sandstone +Clay Plaster (350mm)
W7HC	Hollow Concrete +Camel hair insulation +Cement Plaster (350mm)
W7LS	Limestone +Camel hair insulation +Cement Plaster (350mm)
W7MB	Mud Block +Camel hair insulation +Cement Plaster (350mm)
W7SS	Sandstone +Camel hair insulation +Cement Plaster (350mm)
W8HC	Hollow Concrete +Camel hair insulation +Clay Plaster (350mm)
W8LS	Limestone +Camel hair insulation +Clay Plaster (350mm)
W8MB	Mud Block +Camel hair insulation +Clay Plaster (350mm)
W8SS	Sandstone +Camel hair insulation +Clay Plaster (350mm)

List of symbols

α	Thermal diffusivity (m2/s)
δair	Water vapour permeability of air (kg/m·s·Pa)
δp	Water vapour permeability (kg/m·s·Pa)
Δm	Mass change
$p0$	Standard atmospheric pressure (101325 Pa)
Δp	The water vapour pressure difference=1400 (Pa)
λ	Thermal conductivity (W/m·K)
μ	Water vapour diffusion resistance factor, dimensionless
ρ	Density (kg/m3)
ρa	Density of the water vapour in the ambient air (kg/m3)
ρb	Density of the water vapour in the bamboo surface (kg/m3)
ρair	Density of air (kg/m3)
$\rho bulk$	Bulk density (kg/m3)
ρs	Skeletal density (kg/m3)
ρsat	Saturated density of the water vapour (kg/m3)
ua	The absolute humidity of air (kg/m3)
φ	Relative humidity
ϕ	Porosity
A	Gradient operator
A	The water adsorption coefficient (kg/m2s0.5)
Aex	Exposed area (m2)
C	Total molar concentration (kmol/m3)
Cp	Specific heat capacity (kJ/kg·K)
d	Thickness of the specimen (m)
DAB	Mass diffusivity (m2/s)
Dl	Liquid water diffusivity (m2/s)
$Dwcap$	Capillary saturation liquid water diffusivity (m2/s)
$\dot{E}g$	Energy generation rate in the system
$\dot{E}in$	Heat flow rate in the system
$\dot{E}out$	Heat flow rate out the system
$\dot{E}s$	Energy storage rate
g	Acceleration due to gravity (m/s2)
gi	Internal heat generation (W/m3)
gl	Liquid water flow (kg/m2s)
gm	Moisture flow (kg/m2s)
gv	Vapour flow (kg/m2s)
Gs	Greyscale
h	Heat transfer coefficient (W/m2K)
hm	Water vapour transfer coefficient drove by the difference of water vapour density (m/s)
$hmRH$	Water vapour transfer coefficient drove by the difference of RH (kg/m2·s)
hv	Evaporation enthalpy of water (J/kg)
kJ	Kilo joules
kg	Kilo gram
K	Coefficient of liquid permeability (kg/m·s· Pa)
Ka	Air permeance (s)
l	Length of the specimen in equilibrium state (mm)
$l0$	Length of the specimen in oven dry state (mm)
$\dot{m}$	Water vapour flux density (kg/m2·s)
p	Pressure (Pa)

$p0$	Standard atmospheric pressure (101325 Pa)
pa	Ambient air pressure (Pa)
$psuc$	Capillary suction stress (Pa)
q	Heat flux density (W/m2)
qs	Surface heat flux (W/m2)
ra	Density of air flow rate (m3/m2s)
Rv	Gas constant for water (461.5 J/K·kg)
S	Moisture content in equilibrium state (%)
t	Time (s)
T	The temperature (K)
Ta	Temperature of the ambient air (K)
Tb	Temperature of the bamboo surface (K)
Ts	Constant temperature (ºC)
$T\infty$	Ambient temperature (ºC)
u''	The ratio of water substance to dry wood substance, dimensionless
Uz	The unit vector in the vertical direction
W	Moisture content (kg/m3)
Wcap	Capillary saturation moisture content (kg/m3)
X,Y,Z	Distance in three dimensional Cartesian co-ordinate system (m)
XAs	Constant species concentration
z	Height above a datum level (m)

Chapter One, Introduction

1 Introduction

1.1 Research Background

The Earth Summit set out principles to be implemented according to an action plan (Agenda 21, 1992), requiring nations to develop strategies to achieve sustainability [1]. Subsequently, the Kyoto Protocol was agreed on under the United Nations Framework Convention on Climate Change[2]. Collectively, these developments led to greater global commitment toward meeting sustainable development objectives. Specific actions have since been recommended, leading to increased legislation and regulation of sectors with the highest potential of contributing to attaining these objectives. The construction industry is one of these sectors due to its direct influence on heavy natural resource consumption and environmental and human impacts.

The hygrothermal performance of building envelopes profoundly affects indoor environmental conditions and is critical in attaining an energy-efficient design. Choosing appropriate building envelope materials is one of the most effective ways to manage heat flows, prevent excessive building energy consumption, and maintain a comfortable temperature for the occupants.

A limited number of studies on energy use and thermal comfort within Libyan houses have been completed. However, none of those studies was concerned with the construction materials nor the hygrothermal performance of the construction materials and building envelopes in Libya. Some of those studies are:

"Thermal Comfort and Building Design Strategies for Low Energy Houses in Libya Lessons from the vernacular architecture" [3],

"Comparison study of traditional and contemporary housing design with reference to Tripoli, Libya" [4],

"The Efficient Strategy of Passive Cooling Design in Desert Housing: A Case Study in Ghadames, Libya" [5].

The studies mentioned above attempted to tackle some issues of contemporary architecture in Libya. For example:

- Residents' satisfaction relates to the socio-cultural values of Libyan society.
- Evaluating the sustainability of Libyan houses in terms of suitability to the needs of residents and cultural and climatic conditions.
- The application of passive cooling techniques to improve indoor thermal environment conditions of Libyan houses.

Those studies' findings have shown residents' dissatisfaction with the modern Libyan houses' social, cultural, and environmental aspects.

By investigating the thermal and hygrothermal performance of the common construction materials of Libya, the current study will mainly look at the potential of combining traditional and modern construction materials to introduce novel and hybrid envelope systems that can plausibly help improve the hygrothermal conditions in contemporary domestic buildings in Libya.

1.1.1 Libya's Climate and Topography

Libya is a Mediterranean country located on the Northern Coast of Africa. The population of Libya is 6.4 million as of 2011, mainly occupying the northern coastal area [6]. Libya has a Mediterranean climate categorised by long, warm and dry, often hot and sunny summers with occasional showers and thunderstorms, cool variable winters with dry and cloudy periods, and occasional rain and sunny days [7]. Based on the Koppen climate classification chart [8], the Mediterranean climate is referred to as "Cs" (C= mild temperate, s= Dry summer), as shown in Fig 1.1. In the Mediterranean climate, cooling and heating are required during summer and winter, respectively. Thus, during the design phase, special attention should be given to the following parameters: exposure to the sun, openings size and position, roof and building envelope [9].

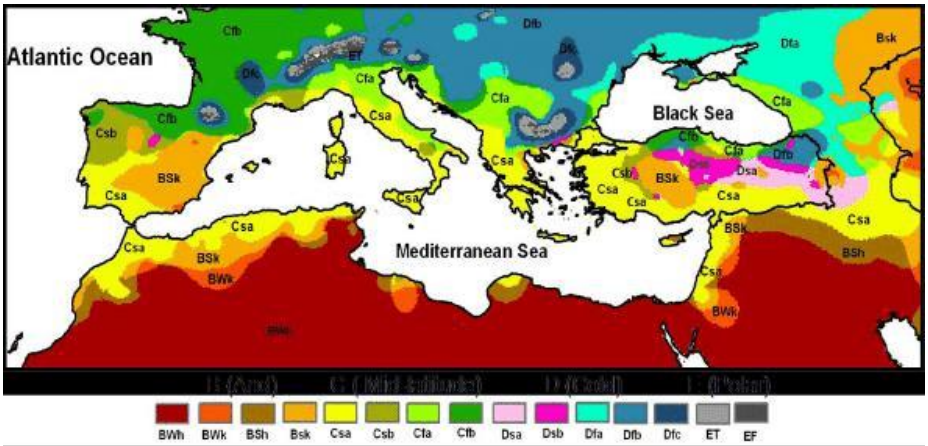


Figure 1-1 Climate Classifications [8]

❖ **Topography**

Libya is a country located in North Africa, with a total land area of approximately 1.76 million square kilometres. The country's topography can be broadly divided into three main regions: the coastal plain, the highlands (mountains), and the Sahara Desert (see Fig 1-2), [6].

The coastal plain is a narrow strip of land that extends along the Mediterranean Sea for approximately 1,100 kilometres. It is characterized by low-lying hills and mountains, with elevations ranging from sea level to approximately 600 meters above sea level. The plain is relatively flat and sandy, with fertile soil in some areas.

The highlands are located in the north-eastern part of Libya and are part of the larger Atlas Mountain range. This region is characterized by rugged terrain, deep valleys, and steep cliffs. The highlands are composed of sedimentary and metamorphic rocks, including limestone, sandstone, and shale.

The Sahara Desert covers approximately 90% of Libya's land area and is characterized by vast expanses of sand dunes, rocky plateaus, and gravel plains. The desert region is relatively flat, with occasional mountains and hills. The Libyan Desert, which is part of the Sahara, is known for its vast expanses of sand dunes and rocky outcroppings. The desert region is also home to several oases, including the Kufra Oasis, which is located in the south-eastern part of the country.

In summary, Libya's topography is diverse and ranges from the flat coastal plain to the rugged highlands and vast Sahara Desert. The country's topography has played a significant role in shaping its history, culture, and economy [6].

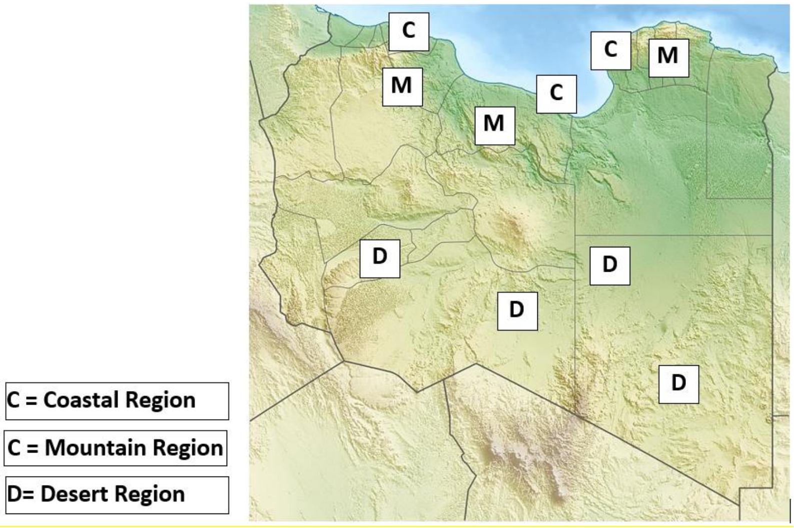


Figure 1-2 Topography of Libya [6]

1.2 Research Scope

The research scope primarily focuses on establishing how traditional and modern Libyan building materials may be used to address sustainable building challenges focused on achieving comfort. The materials research will deal with the hygroscopic and thermal properties of some of the more common traditional and modern building materials used in Libya. The specific challenges that will be addressed are the hygrothermal performance of the building fabric and how it might affect thermal comfort. The variation in hygrothermal comfort performance achieved using traditional and modern construction materials will be addressed through modelling and monitoring. However, the availability of resources, craftsmanship, and applicability of the building materials will not be considered in this study.

1.3 Research Problem, Questions and Hypothesis

The hygrothermal performance of building envelopes in Libya can be improved by developing new and hybrid envelope systems incorporating traditional and modern construction materials. These improvements in the envelope will improve the thermal comfort and energy performance of modern domestic buildings in Libya.

1.4 Research Aim

In many places around the world, including Libya, buildings rely heavily on mechanical heating, ventilation, and air conditioning (HVAC) systems due to their poor performance in regulating temperature and humidity. This leads to higher energy consumption and greenhouse gas emissions. To address this issue, there has been a growing global interest in researching and implementing passive systems that can reduce or eliminate the need for active systems, thereby reducing energy usage and carbon emissions.

The hygrothermal conditions in Libyan houses can be challenging due to the hot and arid climate, which can have significant impacts on building materials and the indoor environment. By investigating the hygrothermal properties of Libyan building materials and their impact on comfort and energy use, this study can provide insights into the design and operation of buildings that are suitable for the local climate conditions

The hygrothermal performance of building envelopes has a profound effect on maintaining indoor environmental conditions. Choosing appropriate building envelope materials is one of the most effective ways to manage heat flows, prevent excessive building energy consumption, and maintain a comfortable temperature and relative humidity for the occupants.

The current study will establish how traditional and modern building materials can enhance hygrothermal comfort within the Libyan context. In other words, and in line with the above, this thesis aims to investigate how traditional and modern building materials might be used to improve hygrothermal comfort in Libyan domestic buildings. This will be explored through a combination of Case Study monitoring, testing of construction materials and hygrothermal simulations.

In order to reduce the number of parameters and variable in the study, this research is restricted to one-storey, single-family domestic buildings with limited modelling and variation.

1.5 Objectives

The aim will be achieved by completing the following objectives:

1) To measure and compare the hygrothermal properties of traditional and modern building materials used in Libya via laboratory measurements.

2) Use the outputs of objective one to assess new wall constructions which combine traditional and modern materials and to optimise these constructions in the hygrothermal simulation software WUFI Plus.

3) To investigate the variation in hygrothermal comfort performance of three Case Study domestic buildings in Libya through the various wall constructions, with reference to current wall constructions.

1.6 Proposed Methods

This thesis uses the following methods to achieve its aim and objectives

1) **Literature Studies**: To investigate the hygrothermal performance, sustainability aspects and the construction materials of Libya's traditional and modern domestic buildings. (Apply to all objectives).
2) **Laboratory Measurements**; To investigate the hygrothermal properties of some of Libya's most common traditional and modern construction materials (Objective 1).
3) **Onsite Monitoring;** To monitor the indoor and outdoor hygrothermal conditions and electricity consumption of the three Case Study Houses (Objective 3).
4) **Calibration of Building Models**; To use the data from step 3 to construct and calibrate the Case Study models in Design-Builder and WUFI Plus (Objective 3).
5) **Building Performance Simulation:** Using the calibrated models from step 4 and the material data from step 2, the hygrothermal performance of the new walls will be evaluated (Objective 2). The impact of changing the wall on the hygrothermal comfort of the Case Study houses will be analysed and reported in Design-Builder and WUFI Plus software (Objective 3).

1.7 Contribution To the Body of Knowledge

At the start of this research, the following was intended; a survey of occupants' thermal comfort, a survey of energy use, and an occupant's behaviour survey. However, due to the time limit and the breakout of COVID-19, these were not completed. The initial results of the survey, along with the ethical approval application (for monitoring the Case Study Houses and conducting the survey) can be found in the Appendices.

This research on the hygrothermal performance of building materials and their impact on energy efficiency and occupant comfort in Libyan domestic buildings has made significant and valuable contributions to the field. By producing a comprehensive database for Libya, this study fills a significant gap in knowledge regarding the hygrothermal properties of Libyan building materials, providing architects and engineers with accurate and representative data that can lead to improved building simulations and design strategies for enhanced occupant comfort and energy efficiency.

Furthermore, the investigation of different wall configurations and materials has revealed insights that can inform professionals and decision-makers in Libya on the selection of appropriate building materials to reduce dependence on mechanical services, lower energy consumption, and reduce carbon emissions while ensuring occupant comfort. The potential impact of these findings goes beyond Libya and can inform sustainable building practices globally.

In conclusion, this research has paved the way for future studies exploring the impact of other building components on hygrothermal performance and the use of traditional and modern building materials in combination for optimal hygrothermal and energy performance, further contributing to the advancement of sustainable building practices.

1.8 Thesis Structure

This research consists of seven chapters (Figure 1-3).

Chapter One, Introduction: covers the introduction, background of the research, hypothesis, aim and objectives, outline of the research methods, research boundaries, and the contribution of the results to the body of knowledge.

Chapter Two, **Literature Review:** reviews the occupant's thermal comfort, theories related to heat and moisture transfer in buildings, literature on construction materials' hygrothermal and physical properties, and computer models' simulation and calibration.

Chapter Three, Methodology: outlines the research methods, equipment, and data types for this research.

Chapter Four, Construction Materials Testing: testing the physical and hygrothermal properties of Libya's modern and traditional construction materials. This chapter will describe the equipment and methods. It will present the results of testing the Moisture Buffer Value ((MBV), (g/m^2 RH%)), Water Vapor Diffusion Resistance Factor ((μ Value), (-)), Sorption Isotherm ((u), (Kg/Kg)), Water Absorption Coefficient ((Aw), ($Kg/(m^2\sqrt{t})$)) of the selected construction materials. The following properties are also included: Density ((ρ), (Kg/m^3)), Thermal Conductivity ((λ), (W/m. K)), Thermal Diffusivity ((α), (m^2/s)), Specific Heat Capacity ((C_p), (KJ/kg. K)).

Chapter Five, Numerical Simulations: this chapter presents the results of calibrating the Case Study models in Design-Builder and WUFI Plus using the data collected from the monitoring. It will also show the results of assessing the impact of the new wall system (using the data from chapter 4) on the hygrothermal performance of the calibrated Case Study models.

Chapter Six, Discussion: is a discussion of the overall results of this thesis against its aim and objectives.

Chapter Seven, Conclusion: the conclusion, recommendation, and future work are presented in this chapter.

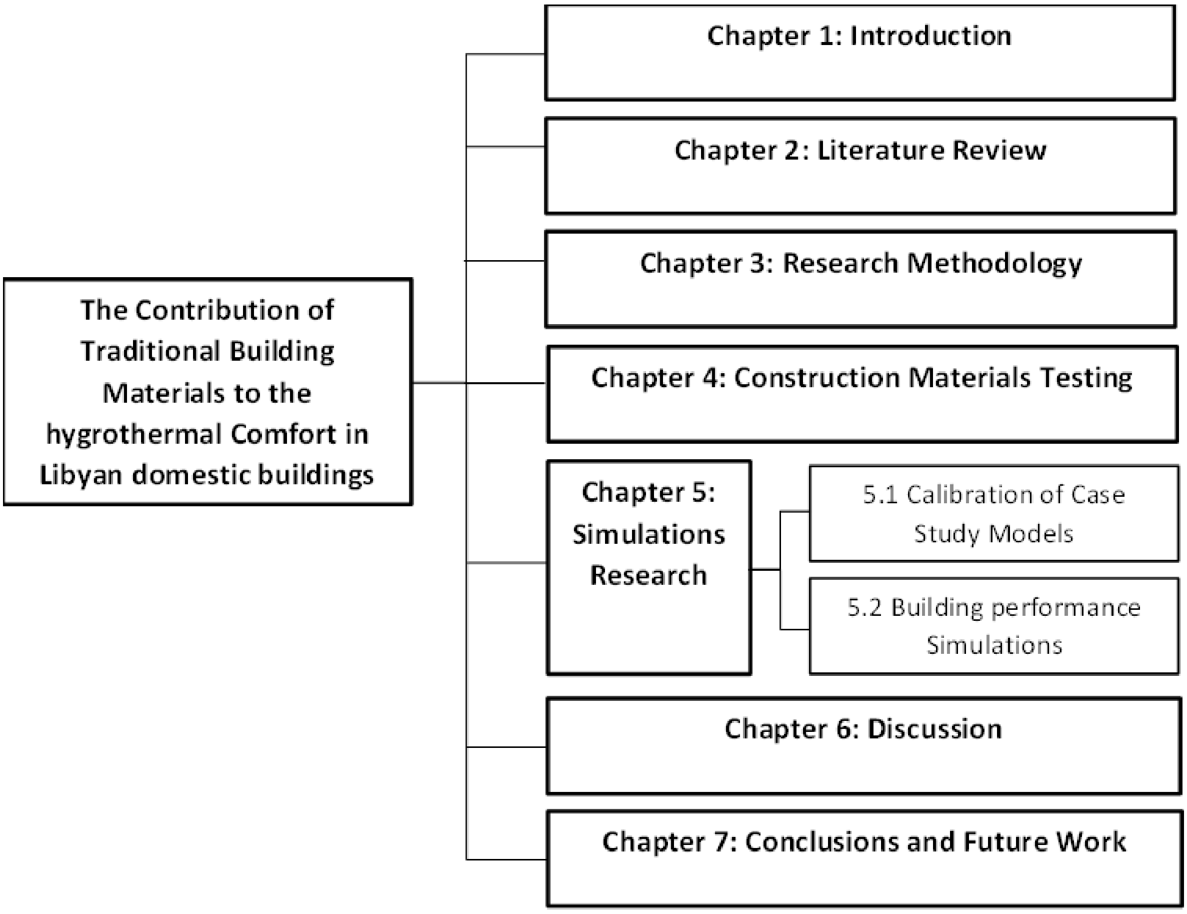


Figure 1-3 Thesis Structure

Chapter Two, Literature Review

2 Literature Review

The thesis focuses on how material choices in building design affect the hygrothermal performance of the building in use and hence the hygrothermal comfort conditions experienced by the occupants. This literature review chapter presents the latest research in these areas to enable the thesis research findings to be presented in context.

This chapter reviews the following;

- Occupants thermal comfort
- Hygrothermal behaviour of building envelope
- Theories related to heat and moisture transfer and storage in buildings and building materials.
- Hygrothermal properties of common Libyan construction materials
- Simulation and calibration of computer models.

2.1 Thermal Comfort

In ASHRAE 55-2013, thermal comfort, also known as “hygrothermal comfort” [10], is "that condition of mind which expresses satisfaction with the thermal environment and is assessed by subjective evaluation". Hence, thermal comfort is a socially determined notion defined by norms and expectations [11].

According to the U.K. Health and Safety Executive (2018), there are the following six environmental and personal factors that affect thermal comfort:

- ***Air temperature:*** the temperature of the air that surrounds the body.
- ***Radiant temperature****:* the heat radiant from a warm object (i.e. the sun, fire, or electrical heating device).
- ***Air velocity*****:** the speed of the air movement within the environment.
- ***Relative humidity*****:** is "the ratio between the actual amount of water vapour in the air and the maximum amount of water vapour that the air can hold at that air temperature" (Hse.gov.uk, 2018).
- ***Clothing level*****:** the level of clothes the person wears that can provide protection from the environment and significantly affect thermal comfort.
- **Metabolic Heat:** the amount of physical movement a person performs results in more Heat produced by the body.

The human body is constantly subject to the influence of the first four parameters with the utilisation of the remaining two parameters (Clothing level and Metabolic heat generation) to achieve thermal comfort. For the human body to regulate itself at a constant temperature, there is a biological thermoregulation process that the body uses against the factors affecting thermal comfort. These include "evaporation of sweat, respiratory evaporation, conduction, convection via the blood, radiation and metabolic storage" [12]. The heat balance equations may be representative of this thermoregulation process [13]:

$$CapM - W = q_{sk} + q_{res} + S \qquad (2.1)$$

Where:

M= metabolic heat production rate (W/m²).
W= rate of mechanical work (W/m²).
q_{sk}=heat loss from the skin (W/m²).
q_{res}=respiratory heat loss (W/m²).
S= heat storage (W/m²).

2.1.1 Measuring Thermal Comfort

Thermal comfort is subjective; therefore, its measurement is more complicated than measuring the environmental and personal factors affecting it. However, there are two measures for thermal comfort analysis [12]:

- Environmental and subjective measures (how the person feels, i.e., hot or cold).
- Tolerance and/or acceptance of thermal conditions.

The British standard BS EN ISO 7730 (2005) [14] specifies a method for calculating the PMV (Predicted Mean Vote) and PPD (Percentage of People Dissatisfaction), two indicators for measuring people's response to the thermal environment.

PMV: is a seven-points (from -3 to +3) thermal sensation scale used to predict the mean value vote for a group of occupants (Table 2-1).

PPD: is an index used to predict the percentage of thermally dissatisfied occupants (i.e., too cold or too warm) and is calculated from the PMV (Figure 2-1).

Thus, occupants' thermal comfort is met when the PMV is between -0.5 and +0.5. (the corresponding PPD is or below 10% - Figure 2-1).

Table 2-1 Seven-Points Thermal Sensation Scale (ISO 7730, 2005)

Thermal Sensation	Vote
+3	Hot
+2	Warm
+1	Slightly Warm
0	Neutral
-1	Slightly Cool
-2	Cool

-3	Cold

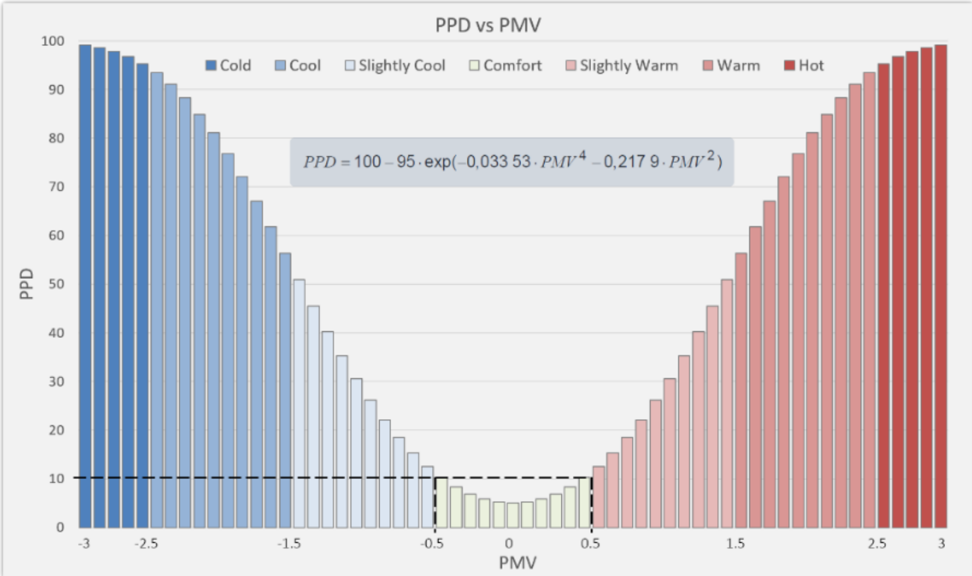


Figure 2-1 Predicted Percentage Dissatisfied (PPD) As a Function of Predicted Mean Vote (PMV) [15]

The research in this thesis addresses factors that impact the air temperature, radiant temperature, and relative humidity aspects of these comfort parameters.

Due to the absence of local thermal model for Libya, The present study rigorously followed established procedures to justify the adoption of the Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) models for assessing thermal comfort in Libya. Specifically, a comprehensive literature review was conducted to identify previous successful applications of the models in similar Mediterranean climates and cultures (Egypt [16], [17] and Morocco [18]), as well as to inform any necessary adjustments to the models' inputs to account for local climate conditions. Additionally, empirical validation was performed through surveys of building occupants to assess the accuracy of the models in predicting thermal comfort in the local context. These efforts ensure the sound application of PPD and PMV models as reliable tools for assessing thermal comfort in Libya [19].

2.2 Hygrothermal Behaviour

Hygrothermal behaviour of material refers to the changes in the physical properties of the material as a result of repeated exposure to absorption, storage and desorption of both heat and moisture [12]. This subsection is therefore, aims to investigate heat and moisture movement and storage in building materials and envelops.

The building envelope is subjected to internal and external environmental loads that include [12]:

- Heat transfer from and to the envelope material through long-wave and short-wave radiation and sensible/ latent heat gains.
- Material heat storage.
- Moisture (liquid and vapour) transfers from and to the material

- ❖ Material's moisture storage.

The indoor hygrothermal loads include:

- ❖ Sensible and heat latent gains from the occupants
- ❖ Moisture vapour from the occupants
- ❖ Heat and moisture generated from mechanical devices

The outdoor hygrothermal loads include:

- ❖ Solar radiation,
- ❖ Groundwater
- ❖ And wind-driven rain and moisture generation.

The interaction of the hygrothermal loads with the building envelope is shown in Figure 2-2 below.

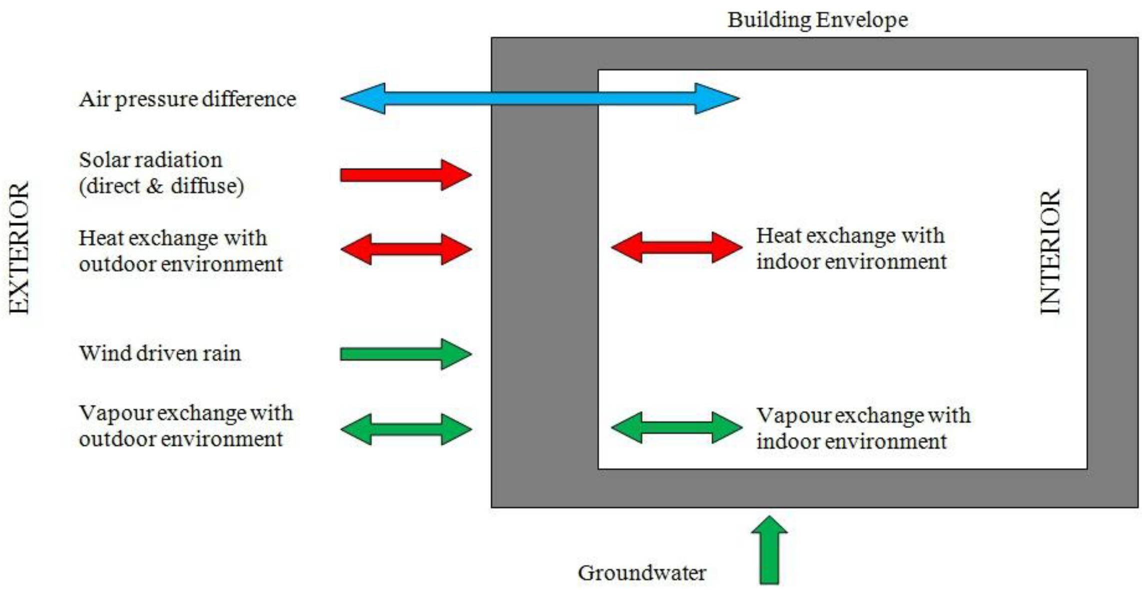


Figure 2-2 Interaction of Hygrothermal Loads with the Building Envelope [12]

The hygrothermal performance of the envelope is determined by the hygrothermal properties of its material [20], mainly the following properties:

- ❖ **Dry and moisture dependant thermal Conductivity (W/m. K)**; The thermal conductivity of a material determines how easily heat can transfer through it. Materials with high thermal conductivity allow heat to move more easily through them, which can result in higher energy costs to maintain comfortable indoor temperatures. Moisture-dependent thermal conductivity is important because the presence of moisture can significantly change a material's thermal conductivity. For example, wet insulation will have a lower thermal conductivity than dry insulation, which can lead to reduced energy efficiency and increased risk of mould growth[21], [22].
- ❖ **Specific heat capacity and moisture-dependent specific heat capacity (J/ (kg. K);** Specific heat capacity refers to the amount of heat energy required to raise the temperature of a material by a certain amount. This property is important because it affects how much heat a material

can absorb and store before it starts to transfer heat to other materials. Moisture-dependent specific heat capacity is important because the presence of moisture can significantly change a material's specific heat capacity. For example, wet materials typically have a higher specific heat capacity than dry materials, which means they can absorb more heat energy before they start to transfer heat to other materials [21], [22].

- **Porosity (m^3/m^3);** Porosity refers to the amount of empty space within a material. This property is important because it affects how much moisture a material can absorb and how easily it can dry out. Materials with high porosity can absorb more moisture, which can lead to increased risk of mould growth and degradation of the material. Materials with low porosity may be more resistant to moisture damage, but they may also be less breathable, which can lead to issues with indoor air quality [23].
- **Bulk density (kg/m^3);** Bulk density refers to the mass of a material per unit volume. This property is important because it affects the weight and structural integrity of a building envelope. Heavier materials may be more structurally sound, but they may also require more energy to transport and install. Lighter materials may be easier to transport and install, but they may be less durable and have lower thermal performance [24].
- **Sorption isotherm (kg/m^3);** Sorption isotherm refers to the relationship between a material's moisture content and its water potential at a given temperature and relative humidity. This property is important because it affects how much moisture a material can absorb and how easily it can dry out. Materials with high sorption isotherms can absorb more moisture, which can lead to increased risk of mould growth and degradation of the material. Materials with low sorption isotherms may be more resistant to moisture damage, but they may also be less breathable [25], [26].
- **Liquid water absorption ($kg/m^2 . s^{0.5}$);** Liquid water absorption refers to the amount of water a material can absorb when it is in contact with liquid water. This property is important because it affects how quickly a material can dry out after it has become wet. Materials with high liquid water absorption may take longer to dry out, which can lead to increased risk of mold growth and degradation of the material [25]–[27].
- **Water vapour permeability ($m^2. s$ P.A.);** Water vapor permeability refers to how easily water vapor can pass through a material. This property is important because it affects how much moisture can enter and exit a building envelope. Materials with high water vapor permeability may allow too much moisture to enter the building envelope, which can lead to moisture damage and poor indoor air quality. Materials with low water vapor permeability may be too

resistant to moisture, which can lead to poor breathability and increased risk of moisture damage [25]–[27].

This subsection explores the hygrothermal behaviour of building materials and envelopes by examining the movement and storage of heat and moisture. It considers various environmental loads that affect the building envelope, such as heat transfer to and from the envelope material, material heat storage, moisture transfers, and material moisture storage. In addition, it identifies indoor and outdoor hygrothermal loads, including heat and moisture generated by occupants and mechanical devices, solar radiation, groundwater, and wind-driven rain and moisture generation.

The importance of envelope materials' hygrothermal properties in determining the envelope's performance is also emphasized. The discussion covers several key properties, including dry and moisture-dependent thermal conductivity, specific heat capacity, porosity, bulk density, sorption isotherm, liquid water absorption, and water vapor permeability.

Overall, the information presented in this subsection is essential for understanding the hygrothermal behaviour of building envelopes and can be used as a foundation for further discussion.

2.2.1 Heat, Air and Moisture Transfer in Buildings

Understanding heat and moisture transfer and distribution through buildings and building materials are essential in evaluating thermal comfort, thermal movement, energy use and avoiding potential moisture problems. In this sub-section, heat and moisture transfer in buildings will be briefly discussed, as those processes are directly involved in building thermal and energy performance assessment [28].

2.2.2 Introduction to Heat Transfer

Heat transfer is the exchange of thermal energy between two systems by heat-dissipating and is the main form of energy transfer in buildings [29]. Naturally, heat energy will flow from the warmer body to the cold medium if there is a temperature difference. However, this is governed by several factors [30]:

- Heat will be transferred from the hot medium to the cold medium
- There must be a temperature difference between the two mediums
- Heat gained by the cold medium is equal to the Heat lost by the hot medium, except for the Heat lost to the surroundings.

Thermal Conductivity (λ), Specific Heat Capacity (C_p) and Thermal Diffusivity (α) are among the functional properties that contribute to the thermal performance of the material [11], as will be discussed later. There are two main types of heat exchange, direct and indirect [16]. Direct heat exchange happens when both mediums are in direct contact. An example of direct heat exchange is a cooling tower, where the water is cooled via direct contact with the air. On the other hand, the indirect heat exchanger accrues when the two mediums are separated by a wall where the Heat is transferred [16].

2.2.2.1 Heat Transfer Process

Heat transfer is the main form of energy transfer in buildings [31]. In general, heat transfers from one body to another in three mechanisms: radiation, conduction and convection [32]. Heat transfer via radiation and convection are considered during the numerical simulation; however, it was not necessary to experimentally investigate these properties. In the context of this thesis, heat transfer by conduction is of interest.

Conduction heat transfer can be defined as the "transfer of energy between neighbouring molecules due to a temperature gradient" [12]. The first law of thermodynamics can be stated [31]:

$$\dot{E}_{in} + \dot{E}_g = \dot{E}_{out} + \dot{E}_s \qquad (2.2)$$

Where:

$\dot{E}_{in}$= rate of heat flow in the system
$\dot{E}_g$=rate of energy generation in the system
$\dot{E}_{out}$= rate of heat flow out of the system
$\dot{E}_s$= rate of energy storage

For the three-dimensional Cartesian coordinate system, Equation (2.2) can be transferred into [31]:

$$\lambda\left(\frac{\partial^2 T}{\partial X^2} + \frac{\partial^2 T}{\partial Y^2} + \frac{\partial^2 T}{\partial Z^2}\right) g_i = pC_p \frac{\partial T}{\partial t} \qquad (2.3)$$

where:

λ= thermal Conductivity (W/m. k)
X, Y, Z= Distance in three-dimensional Cartesian coordinate system (m)
T= temperature (K)
g_i= internal heat gain generation (W/m^3)
ρ= density (kg/m^3)
C_p= specific heat capacity (J/kg. K).
t=time (s).

Heat transfer can be a steady or transient process. in the transient state, the heat flow varies with time. In the steady-state, heat flow happens when the temperature and heat flow reach a stable equilibrium condition that does not change with time [33]. For the steady-state heat transfer, and if the internal heat generation is neglected, Equation (2.3) can be transformed to [31]:

$$\frac{\partial^2 T}{\partial X^2} + \frac{\partial^2 T}{\partial Y^2} + \frac{\partial^2 T}{\partial Z^2} = 0 \qquad (2.4)$$

As the actual heat transfer is mostly not steady-state, Equation (2.3) is usually more often utilized to describe the heat transfer through the building envelope components [31].

2.2.2.2 Moisture Transfer Process

Moisture flow through the building envelope can be divided into vapour flow and liquid flow [34]. Equation (4.2) describes the moisture transfer in buildings [31].

$$g_m = g_v + g_i \qquad (2.5)$$

Where:
g_m= moisture flow (kg/m²s)
g_v= vapour flow (kg/m²s)
g_i=liquid water flow (kg/m²s)

The vapour flow (g_v) can be expressed by the following Equation [35]:

$$g_v = (-\delta_p)\nabla p + r_\alpha v_\alpha \qquad (2.6)$$

Where:
δ_p=Water vapour permeability (kg/m·s·Pa)
p=Pressure (Pa)
r_α=density of airflow rate (m³/m²s)
v_α=The humidity by volume of air (kg/m³).

The density of airflow rate ($\boldsymbol{r_\alpha}$) can be calculated by: [36], [37] and [38].

$$r_\alpha = -K_a \nabla (P_a - p_a g z U_z) \qquad (2.7)$$

Where:

K_a= air permeance (s)
P_a= overall air pressure
p_a= density of air (kg/m³)
g= acceleration because of gravity (m/s²)
z= height above Datum level (m)
Uz= unit vector in the vertical direction.
∇= gradient operator ∇T=$\frac{\partial T}{\partial x}$ in one dimension.

The following Equation is for the liquid water flow (gi), which is:

$$gi = K \nabla P_{suc} \qquad (2.8)$$

Where:

K= Coefficient of liquid permeability (kg/m· s· Pa)
$\boldsymbol{P_{suc}}$= Capillary suction stress (Pa).

2.2.2.3 Heat and Moisture Balance Equation

By integrating the equations (1-6), the Heat, moisture and air transfer can be described as follow [39], [40].

$$\frac{\partial H}{\partial T}\frac{\partial T}{\partial t} = \nabla(\lambda \nabla T) + h_v \nabla\left[\delta_p \nabla(\varphi P_{sat}\right] \qquad (2.9)$$

$$\frac{\partial w}{\partial \varphi}\frac{\partial \varphi}{\partial t} = \nabla[D_i \nabla \varphi + \delta \nabla(\varphi P_{sat})] \qquad (2.10)$$

Where:

$\frac{\partial H}{\partial T}\frac{\partial T}{\partial t}$= Heat storage capacity (J/m^3. K)
T= Temperature (K)
t= Time (s)
λ= Thermal conductivity (W/m. K)
h_v= Evaporative enthalpy of water (J/kg)
δ_p= Water vapour permeability (kg/m. s. Pa)
φ= Relative humidity (-)
P_{sat}= Saturated pressure of water vapour (Pa)
$\frac{\partial w}{\partial \varphi}$ = Moisture storage capacity of building material (kg/m^3)
D_i= Liquid water diffusivity (m^2/s).

The main properties that influence the hygric behaviour of material include bulk density (ρ), Porosity (ϕ), sorption isotherm, water permeability (δ) and water absorption (Aw). The following subsections will review some of the key input parameters of construction materials related to heat and moisture transfer and storage functions.

2.2.3 Hygrothermal Properties of Construction Materials

This section discusses the following materials' properties:

- Thermal Conductivity (λ), (W/m. K).
- Specific Heat Capacity (C_p), (K.J./kg. K).
- Thermal Diffusivity (α), (m^2/s).
- Dry Density (ρ), (Kg/m^3).
- Moisture Buffer Value (MBV), (g/m^2 RH%)
- Water Vapor Diffusion Resistance Factor (µ Value), (-)
- Sorption Isotherm (u), (Kg/Kg)
- Water Absorption Coefficient (Aw), ((Kg/(m^2√t))

2.2.3.1 Thermal Conductivity (λ)

In the international standard [41], Thermal Conductivity (λ) is defined as the "total amount of heat transferred from one side of the specimen to the other for a given temperature difference in defined testing conditions". The unit of thermal Conductivity is (w/m-k) and is given by the following Equation:

$$\lambda(\mathrm{W/m/K}) = \frac{Q}{Ft\ \frac{\Delta T}{h}} \qquad (2.11)$$

where:
Q= is the amount of conducted Heat
F= area through which Heat is conducted
t= time of Heat conducting
ΔT= temperature difference
h= material thickness.

Several factors can affect the Thermal Conductivity of a material [42]. Depending on the material, the main factors include the density of the material, moisture content, and ambient temperature. Other factors such as air velocity, material ageing, the material's thickness, and pressure can also impact the Thermal Conductivity of materials [43].

Each of the factors mentioned above can affect the thermal Conductivity of materials differently. It was found that the Thermal Conductivity of materials increases with increasing the temperature, moisture content, air velocity across the surface and ageing of the material [44], [45], [43], [46] and [47]. The research also showed that Thermal Conductivity could be reduced by increasing the Density [48], [49]. Although thermal Conductivity is not dependent on the thickness of the material, it was found that increasing material thickness can increase its thermal resistance [50].

Thermal Conductivity is the ability of a material to conduct Heat and is one of the critical parameters used to assess the thermal insulation properties of building materials; the lower the Thermal Conductivity, the lower the heat transfer through the building envelope [51]. In their research, [43] presented four classifications of materials based on their Thermal Conductivity:

- Materials with thermal Conductivity from 0.1 w/(w. K) and lower than 0.3 w/(w. K) are classed as "very good".
- Materials with thermal Conductivity from 0.3 w/(w. K)- 0.5 w/(w. K) are "moderate"
- Materials with thermal Conductivity of 0.7 w/(w. K) and higher are "less effective".
- Materials with a thermal conductivity lower than 0.1 w/ (w. K) can be classed as "thermal insulation materials".

2.2.3.1.1 Measuring Thermal Conductivity

Generally, there are two methods for measuring the Thermal Conductivity of bulk materials: the steady-state method and the transient method. The principle of the steady-state method is that it measures thermal Conductivity by establishing a temperature difference that does not change with time. On the other hand, the transient method measures the time-dependent process [52]. Each of the methods mentioned above has it is own advantages and disadvantages and is valid for a limited range of materials, depending on the thermal properties, sample configurations, and measurement temperature.

2.2.3.1.1.1 STEADY-STATE METHODS

Thermal Conductivity can be measured in the steady-state method by measuring the thermal difference ΔT under the steady-state heat flow Q through sample A. There are four approaches under the steady-state method [44]. These are the absolute, comparative cut bar, radial heat flow, and parallel thermal conductance. Table 2-2 below is a comparison between the different methods.

Table 2-2 Steady-state Methods for Measuring Thermal Conductivity

Method	Principle	Calculations	Notes	Ref.
Absolute technique	• *A test specimen with knowing (length) is placed between a heat source and heat sink* • *The sample is then heated by a heat source with a steady-state knowing power* • *Temperature drop across the length of the specimen is then measured with a temperature sensor* • *Thermal Conductivity can be measured using equations (20.2) and (21.2).*	$\boldsymbol{k = \frac{QL}{A\Delta T}}$ $\boldsymbol{Q = p - Q_{loss}}$ *Where: Q= heat flow through the sample* *A= Cross-sectional area of the sample* *L= distance between the temp sensors* *Δ= temp difference* *P= applied heating power at the heat source side* *Q loss= parasitic heat losses due to radiation, conduction, and conviction of the ambient*	• *Used for samples that have rectangular or cylindrical shapes* • *Control parasitic heat losses to less than %2*	*ASTM C177* *EN 12667* *ISO 8302*
Comparative cut bar technique,	• Measurement configurations are like the absolute technique • *At least two temp sensors are to be deployed on each bar* • *Standard material with known thermal Conductivity is mounted in series with the test sample.* • *Once the amount of heat flow through the standard materials equals the heat flow through the test sample, thermal Conductivity is given by equation (22.2).*	$\boldsymbol{k_1 = k_2 \frac{A_2 \Delta T_2 L_1}{A_1 \Delta T_1 L_2}}$ Where subscripts 1 and 2 are associated with the sample and the standard material, respectively.	• *Efforts to ensure equal heat flow between the standard material and the test specimen.* • *No need to measure heat flow which eliminates Errors associated with heat flow measurement* • *The other type of comparative technique is the heat flow meter method, which is used for testing materials with low Thermal Conductivity, such as insulation materials.*	*ASTM E1225* *For the heat flow method:* *ASTM C518* *ASTM E1530* *EN 12667*
Radial heat flow method	• *The cylinder-shaped specimen is internally heated at the axis*	$\boldsymbol{k = \frac{Q ln(r_2/r_1)}{2\pi H \Delta T}}$	• *Cylindrical sample*	*ASTM C335* *ISO 8497*

	• *As heat flow outwards, a steady-state gradient in the radial direction is established* • *Thermal Conductivity can be calculated from Equation (23.2)*	*where: r1 and r2 = radius where the two temp sensors are located* *H= sample hight* *The ΔT= temperature difference between the temperature sensors*	• *Used for measurement at very high-temperature cylindrical s (e.g.>1000K)*
Parallel thermal conductance technique	• *A specimen holder is used between the heat source and the heat sink* • *The thermal Conductivity of the specimen holder is measured first to identify heat losses through the specimen holder* • *The test specimen is then attached to the holder, and the thermal Conductivity of the sample is measured again*	Thermal conductance can be obtained from the difference in the measurement of the thermal Conductivity of the specimen and the specimen holder Thermal Conductivity is then calculated from thermal conductance by multiplying the specimen length and dividing by the sample cross area section.	*Used for measuring the thermal Conductivity of small needle-like samples*

2.2.3.1.1.2 TRANSIENT TECHNIQUE

In the transient technique, the Heat is supplied either regularly, resulting in periodic (phase signal output) temperature change, or as a pulse, which results in transient (amplitude signal output) change in the sample's temperature [53]. The four standard transient techniques are pulsed power, hot-wire, transient plane source, and laser flash thermal diffusivity [53]. Table 2-3 below is a comparison of the four methods.

Table 2-3 Transient Methods for Measuring Thermal Conductivity

Method	Principle	Calculations	Notes	Standards
Pulsed power technique	• *The tests specimen is held between a heat source and a heat sink* • *A period of 2T periodic electric current is applied to the heat source.* • *The heat current is then supplied as either a square wave of constant-amplitude current or a sinusoid wave* • *The temperature of the heat sink changes slowly during the experiment resulting in a slight temperature gradient between the heat source and the heat sink*	*The heat balance is given as follows:* $Q = C(T_h)\frac{dT_h}{dt} = R_e(T_h)I^2(t) - K\left(\frac{T_c+T_h}{2}\right)\Delta T(t)$ *Where:* *Re (Th) is the electrical resistance of the heater, which changes with the temperature*	• *Samples are usually cylinder or rectangular-shaped.* • *Can measure wide ranges of temperatures, ranging from 1.9-390k* • *For thermal Conductivity, it Can measure as low as 0.004 W/m.K for ZrW2O8 at a temperature of 2K.* • *The uncertainty is reported as less than 3%.*	

	• A calibrated Au-Fe chromel thermocouple can then measure the temperature gradient			
Hot-wire method	• The linear heat source (i.e. hot wire) is embodied in a specimen with knowing dimensions. • Temperature rise will occur in the test specimen as a result of the electric current passing through the hot wire • The Thermal Conductivity can then be obtained from the temperature change at a known distance over known time intervals.	• Transit temperature: $T(r,t) = \frac{p}{4\Pi kL}\left[In\,(\frac{4\alpha t}{r^2}) - y\right]$ • Temperature rise form in the test specimen from time t1-t2: $\Delta T = T(t_2) - T(t_1) = \frac{p}{4\Pi kL} In\left(\frac{t_2}{t_1}\right)$ • Thermal Conductivity can be obtained from the following: $k = \frac{p}{4\Pi[T(t_2)-T(t_1)]L} In(\frac{t_2}{t_1})$	• The method can be used to measure the Thermal Conductivity of solids and powders and can be used for liquids, and has been commonly used to measure low thermal conductivity materials • If appropriately applied, the method can achieve an uncertainty of less than 1%	ASTM C1113, ISO 8894 For the needle prop method: ASTM D5930, ASTM D5334
Transient plane source method (TPS)	• A thin metal strip or disk is used as both the heat source and temperature sensor • The disk is then placed between two identical test specimens • The remaining surfaces of the test specimens should be thermally insulated • The metal disk is then heated up by applying a small constant current • The thermal properties of the test specimen can be determined from the temperature change for a short period (generally for a few seconds)	Fitting the temperature curves by equations (28.2) and (6) to the measured ΔT renders the inverse of thermal Conductivity $1/k$ $\Delta \boldsymbol{T}(\emptyset) = \frac{\boldsymbol{Q}}{\boldsymbol{\pi^{1.5}\, rk}} \boldsymbol{D}(\emptyset)$ $\emptyset = \sqrt{\frac{\boldsymbol{t\alpha}}{\boldsymbol{r^2}}}$ Where: r= sensor radiation D (∅)=dimensionless theoretical expression of the time-dependent increase describes heat conduction of the sensor	• Thin slap-shaped specimens • Measures materials with thermal Conductivity of 0.005-500 W/m.K	ASTM D7984 ISO 22007-2
Laser flash method for thermal Diffusivity	• The test specimen is usually sprayed with a layer of graphite • On the front side, the graphite works as an absorber; at the back, the graphite layer acts as an emitter. • The front side of the sample is equally heated using an instantaneous heat source • A detector is used to measure the time-dependent temperature change at the rare side of the specimen	Temperature increases on the rare side: $T(t) = \frac{q}{pc_p d}\left[1 + 2\sum_{n=1}^{\propto}(-1)^n\, exp(\frac{-n^2\pi^2}{d^2}\ \alpha t)\right]$ Where: d= thickness of the test specimen α = thermal diffusivity To simplify Equation (31.2): $W(t) = T(t)/T_{max}$ (32.2), $\eta = \pi^a \alpha t/d^2$ T_{max} = max temperature at the rare side of the specimen when combining equations 32.2 and 33.2: $W = 1 + 2\sum_{n=1}^{\infty}(-1)^n exp(-n^2\,\eta)$ Where: W= 0.5, η	• The method can achieve remarkable accuracy • Usually, for thermal Conductivity, the material is solid planar shaped • Thermal Conductivity can be measured for a wide range of temperatures (-120°C-2800°C) with an error of less than 3%	ASTM E1461 ISO 22007-4

	Thermal Diffusivity is calculated from: $\alpha = \frac{1.38d^2}{\pi^2 t_{1/2}}$ *Where* $\boldsymbol{t_{1/2}}$*= time required for heating the specimen to one-half maximum temperature at the rare side* *Thermal Conductivity can be obtained from:* $\boldsymbol{k = \alpha p c_p}$	• *Results can be obtained within 1-2 seconds for most solids.*

In this research, the transient test method, using "ISOMET 2114 Thermal Properties Analyser" is used to obtain the thermal conductivity, thermal diffusivity and heat capacity of the selected material samples.

2.2.3.2 Specific Heat Capacity $(\boldsymbol{C_p})$

Specific heat capacity is a physical property defined as the "quantity of heat necessary to raise the temperature of a unit mass of material by 1K at constant pressure". [54]. Specific heat capacity is also one of the critical input parameters in the mathematical simulation of heat transfer [31] and is given by the following Equation:

$$C_p = m^{-1}Cp = m^{-1}(dQ/dT)p \qquad (2.12)$$

Where:

- m= mass of the material,
- C_p = the heat capacity,
- *dQ*= the quantity of Heat necessary to raise the temperature of the material by dT, subscript
- p= indicates an isobaric process,
- C_p is expressed in ($kJ\cdot kg^{-1}\cdot K^{-1}$) or ($J\cdot g^{-1}\cdot K^{-1}$).

2.2.3.3 Thermal Diffusivity (α)

Thermal Diffusivity is one of the physical properties of materials which can be defined as the ratio of the thermal Conductivity to the specific heat capacity of the material [31]. Thermal Diffusivity is an essential input in the transient heat conduction equation [31]. The higher the Thermal Diffusivity of the material, the quicker that material reaches a new equilibrium condition [31].

The following equations give thermal Diffusivity:

$$\alpha \nabla^2 T = \frac{\partial T}{\partial t} \qquad (2.13)$$

$$\alpha = \frac{K}{C_p \rho} \qquad (2.14)$$

Where: α= thermal diffusivity (m²/s), T= temperature (K), t= time (s), K= thermal conductivity (W/m. K), ρ= density (kg/m³), C_p= specific heat capacity (J/kg. K).

2.2.3.4 Density (ρ)

In addition to being a physical property, density is essential in defining and analysing objects' mechanical and thermal properties [31]. Density is a fundamental material property defined as mass divided by volume [55].

Although the definition of density is straightforward, accurate density determination for some materials can be challenging to attain in some occurrences [56]. This is due to several factors, such as volume irregularities, moisture content of the sample, Porosity, and material permeability [57]. The definition of density itself brought more complications to the process by the number of definitions of density. This can be seen in the British standards, which have fourteen different definitions of density [58]. For this research, the density of the selected construction material samples will be measured according to the British standard BS EN ISO 12570 [59].

2.2.3.5 Moisture Buffering

Relative humidity significantly impacts the indoor climate and can affect indoor air quality, thermal comfort, working efficiency and the health of the occupants [60],[61]. When the indoor relative humidity (RH) is below 40%, there is a risk of increasing concentration of toxic pollution in the air, which can cause and increase the chances of health issues. In contrast, humidity higher than 60% can cause thermal discomfort and provides conditions for mould growth and other issues [62]. To minimise these risks and to keep the temperature and humidity levels under control, mechanical equipment and energy-consuming air conditioning systems are often used. It is possible to improve, to some degree, indoor thermal conditions and likely reduce energy consumption by passively controlling indoor humidity [63]. Building materials and furniture in contact with the indoor air of occupied buildings can positively impact moderating the fluctuations of the indoor humidity levels [64]. Vapour-responsive materials, such as Clay and timber, can be used to provide some degree of control of indoor humidity levels due to their ability to absorb and desorb moisture [62]. This ability is called moisture buffering and is sometimes referred to as humidity buffering [65], which can be defined as "the ability of surface materials in the indoor environment to moderate the indoor humidity variations through adsorption or desorption" [60]. The interior surfaces of the building envelope (walls, ceiling, and floor) and the furniture will both impact the moisture and humidity levels in the room, not only the moisture conditions of the indoor air but also moisture conditions in the material acting as moisture buffers [65].

It was also found that moisture buffering affects energy consumption during heating and cooling seasons [62]. In winter, hygroscopic materials can generate latent Heat as they absorb moisture from the air, reducing heating energy consumption. During the summer, hygroscopic materials can keep the humidity levels low and decrease the room enthalpy, reducing the cooling energy consumption [62].

For these reasons and more, it is essential to study, categorise and define the moisture-transmitting and buffering properties of absorbent porous materials, which is the objective of this sub-section.

2.2.3.5.1 Definition of Moisture Buffering Value (MBV)

According to [66], Moisture Buffering Value (MBV) represents the amount of moisture absorbed or desorbed by a material when subjected to repeated daily changes in relative humidity between two given levels. The unit for MBV is kg/ (m^2. % R.H.). Moisture Buffer Value (MBV) can be used to describe the ability of building materials and systems to exchange moisture with the indoor environment" [64]. MBV is a measure of the amount of moisture transported to and from a material at a given exposure, and thus, is mainly but not only a material property [64]. MBV is determined by several factors, such as the outdoor climate, ventilation, moisture buffering of the surface materials and furniture within the room, the possibility of condensation on the cold surfaces and finally, the variation of these factors with time [65]. In short, the MBV concept can be used when assessing the material and systems' ability to regulate humidity variation in their surrounding environment [64].

2.2.3.5.2 Different Levels of Moisture Buffering

"The moisture buffering performance of a room is the ability of the materials within the room to moderate variation in the relative humidity" [64]. The variations in the relative humidity can be time-related, as they vary between day and night and from season to season, and can also be for different spatial levels [65]. Regarding spatial variation, the moisture buffering capacity is divided into three levels [64] (Figure 2-3): material, system, and room.

At the material level, the MBV is based on the material properties obtained under a steady-state and equilibrium condition without considering the influence of the surrounding environment [67]. At the system level, MBV should be dealt with as a parameter that describes the behaviour of different components. These components can be the interior surfaces of the materials with the surface coating.

[68]. At the system level, the period for the moisture variation must be considered, which is not the case at the material level since the properties are acquired from a steady state [68]. Similarly, external influences, such as air velocity, would significantly impact the results [68]. The parameters included are considered at the room level, such as the heating and cooling, ventilation and building materials and interior surfaces.

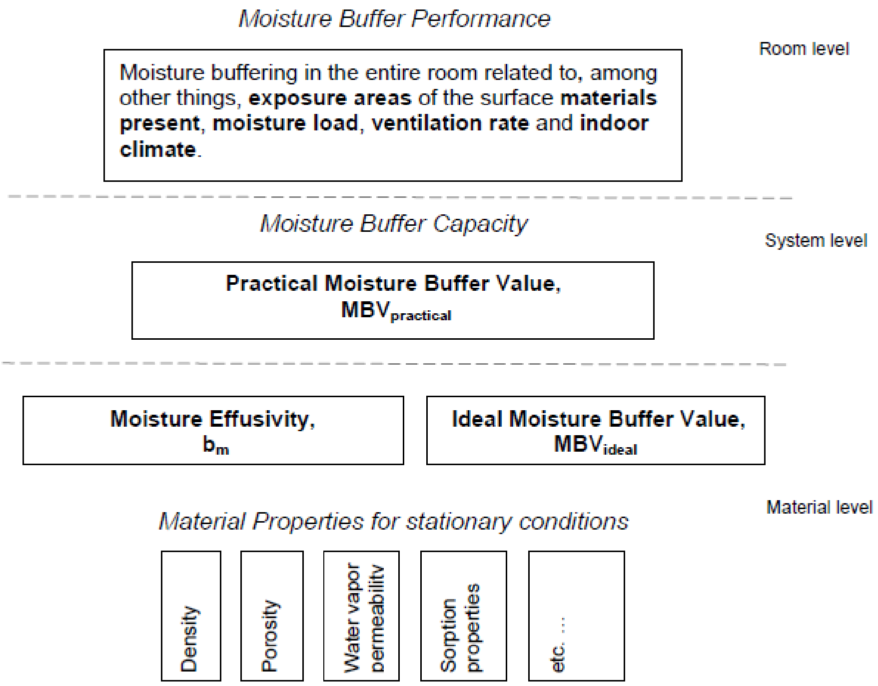


Figure 2-3 Levels of Moisture Buffering Capacity [69]

2.2.3.5.3 Moisture Effusivity (bm)

Moisture effusivity (bm) is used to describe the material's capability to exchange moisture with it is surrounding when the surface of that material is subjected to a sudden change in the relative humidity [64] and is given by the following Equation:

$$b\_m = \sqrt{\frac{\delta_P . \rho_0 . \frac{\partial u}{\partial \varphi}}{p_s}} \qquad (2.15)$$

Where:

δ_P= water vapour permeability [kg/(m.s.Pa)]
ρ_0= the dry density of the material [kg/m^3]
$\mathcal{U}$= moisture content [kg/kg]
φ= relative humidity [-]
p_s= saturated vapour pressure [Pa].

Apart from the saturated pressure p_s, Given the test condition, all the other parameters in the moisture effusivity are standard material properties [64].

2.2.3.6 Ideal Moisture Buffer Value (MBV_{Ideal})

Ideal moisture buffer value is defined as "the theoretical determination of moisture buffer value (MBV) based on its moisture effusivity, period of moisture uptake and saturation vapour pressure" [69] and is given by the following Equation:

$$G(t) = \int_0^t g(t)dt = b_m.\Delta p.h(\alpha)\sqrt{\frac{t_p}{\pi}} \quad (2.16)$$

Where:

$$h(\alpha) = \frac{2}{\pi}\sum_{n-1}^{\infty}\frac{sin^2(n\pi\alpha)}{n^{3/2}} \approx 2.252[\alpha(1-\alpha)]^{0.535} \quad (2.17)$$

α [-] = the fraction of the time for the high humidity level period, for the case of 8 and 16 hours α= 1/3, and therefore, the h(α)= 1.007. hence, a more straightforward form of Equation (2.17) is:

$$G(t) \approx 0.568.b_m.\Delta p\sqrt{t_p} \quad (2.18)$$

From the above, the ideal moisture buffer value can be expressed as:

$$MBV_{Ideal} \approx \frac{G(t)}{\Delta RH} = 0.568.b_m.P_s.\sqrt{t_p} \quad (2.19)$$

MBV can be either pure material property or a practical performance property. The pure material property is only valid for a homogenous material. It can only be measured under ideal conditions where the moisture flows, in or out of the material, and face no resistance from the convective moisture transfer process [64]. However, when testing the material's properties in practice, either in the typical indoor environment or in the climate chamber, there is some convective surface resistance at the material surfaces [64]. Furthermore, many building products are not homogenous and most likely to contain some surface treatment.

2.2.3.6.1 Practical Moisture Buffer Value (MBV Practical)

$MBV_{Practical}$ (The practical Moisture Buffer Value) indicates the amount of water absorption or desorption per open surface area of material with respect to time when it is exposed to variations in surrounding air's relative humidity. The unit for $MBV_{Practical}$ is kg/(m²·% RH) [64].

The practical moisture buffer value categorises materials based on the experimental method, where the test specimen is exposed to cycle change in relative humidity [64]. The sample is first exposed to 75% R.H. for 8 hours and then to 33% R.H. for 16 hours (see section 3.4.2.1.).

2.2.3.6.2 Moisture Penetration Depth

The penetration depth is defined as "the depth where the amplitude of moisture content variations is only 1% of the variation on the material surface" [64].

An approximation of the penetration depth is given in the following Equation:

$$d_p 1\% = 4.6\sqrt{\frac{D_w . t_p}{\pi}} \qquad (2.20)$$

Where:

Dw= moisture effusivity of the material
t_p= cycle time
$d_p 1\%$= is the thickness of the material at %1 penetration depth.

2.2.3.6.3 Measuring Moisture Buffer of Materials

Several methods and standards have been developed to measure and quantify the dynamic sorption capacity of materials. Some of these methods are the NORDTEST protocol [64], the British standard (BS ISO 24353, 2008) [70], and the Japanese standard (JIS A 1470-1, 2014) [71].

The tests are conducted in a controlled environment under a constant temperature and cyclic relative humidity (RH). The basic and common principle of these standards is to constantly monitor the change in the mass of a test sample undergoing a cyclic relative humidity fluctuation [48]. Water adsorption and desorption are indicated through the change in the mass of the test specimen during the humidity cycles. Even though these methods' principles are the same, there are a few differences in the boundaries and test conditions. Table 2-4 below presents and compares some differences between the test protocols of moisture buffering [63].

Table 2-4 Main Differences Between Moisture Buffering Protocols

Protocol	RH level	Time cycles(h)
NORDTEST protocol [64]	75%-33%	8h of high R.H., followed by 16h of low R.H.
BS ISO 24353, 2008 [72]	55%-33% 75%-53% 95%-75%	12 – 12
JIS A 1470-1, 2014 [73]	55%-33% 75%-53% 93%-75%	24 – 24

2.2.3.7 Water Vapour Resistance Factor (µ value)

The Water Vapour Diffusion Resistance Factor (µ-value) measures the material's ability to let water vapour pass through and is measured in compression to the properties of air [74].

The µ value can be expressed as follows;

$$\mu = \frac{\delta_\alpha}{\delta} \qquad (2.21)$$

where: δ_α= water permeability in air, δ= Vapour permeability of porous system in the material.

The equivalent air layer (sd) is expressed by:

$$S_d = \mu . d \qquad (2.22)$$

Where: d represents that material's thickness.

From the above, the μ-value can be defined as the amount of water vapour passing through a unit area of material per unit of vapour pressure per unit of time [75].

The u-value of material is dependent on the following [35]:

- The open-pore area of each unit surface of a material.
- The thickness of the material
- The relative humidity levels

2.2.3.7.1 Measuring Water Vapour Resistance Factor (u-value)

The Water Vapour Resistance Factor (μ-value) can be measured by following the British standard [76]. The basic principle is based on the climate chamber method, where the specimen is sealed to an open side of a test cup containing either saturated salt solution (for the Wet Cup test) or desiccant (for the Dry Cup test). The assembly is then placed inside a temperature and relative humidity-controlled test chamber; because of the difference in the partial vapour pressure between the chamber and the test cup, the vapour flow through the specimen. The rate of transmitted water vapour can be determined by periodic weighing of the test assembly.

2.2.3.8 Sorption Isotherm

Materials tend to approach equilibrium with the temperature and vapour pressure of the surrounding environment, and to reach this equilibrium; the material will either gain or lose moisture to the environment, depending on whether the vapour pressure of the surrounding environment is higher or lower than the vapour pressure of the material. [77] the process of gaining moisture is called adsorption, and the process of losing moisture is called desorption.

Sorption Isotherm describes the thermodynamic relation between the water activity and the equilibrium of the moisture content of the material at constant temperature and pressure [78]. Sorption Isotherm is essential for understanding the moisture transfer mechanism of construction materials. Furthermore, Sorption Isotherm is necessary for analysing water vapour transport between the indoor air and the interior surfaces of buildings [79].

2.2.3.8.1 Sorption Isotherm Shapes

Sorption Isotherm represents the relation between moisture uptake and the external psychrometric conditions (relative humidity and temperature) [12]. In K. Kielsgaard Hansen (1986) [80], sorption isotherm was groped into six different classes (Figure 2-4):

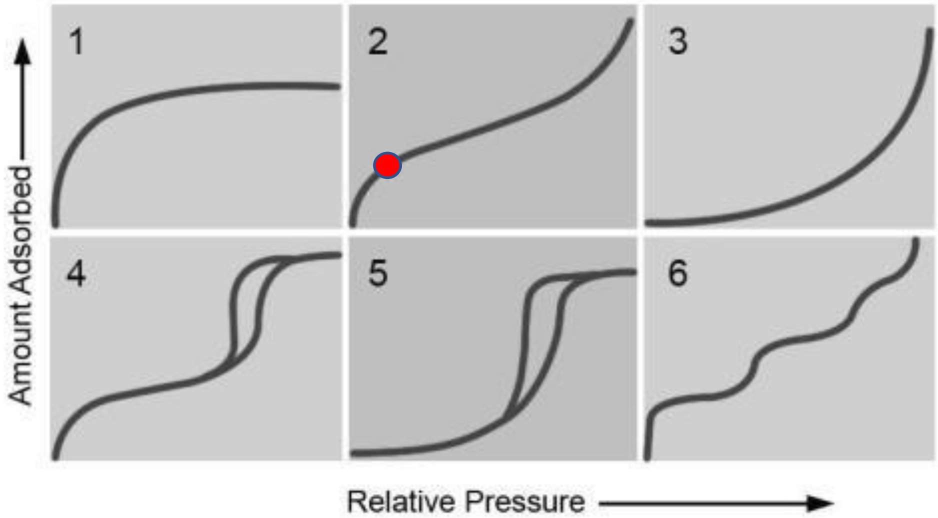


Figure 2-4 Different Types of Isotherm [81]

- ***Type 1:*** indicates a microporous adsorbent with a relatively small external surface. In *Type 1*, The moisture uptake value is determined by the accessible micropore volume rather than the internal surface area [81], [80].
- ***Type 2:*** Shows a non-porous or microporous adsorbent with adsorbent-adsorbate interaction. The point on the isotherm in *Type 2* indicates the completion of monolayer adsorption and the begging of multilayer adsorption [81], [80].
- ***Type 3:*** Indicates a microporous system with a weak adsorbent-adsorbate interaction [81], [80].
- ***Type 4:*** Result of capillary condensation in a mesoporous adsorbent [81], [80].
- ***Type 5:*** Indicates a porous adsorbent with weak adsorbent-adsorbate interaction [81], [80].
- ***Type 6:*** Stepwise multilayer adsorption on a uniform non-porous adsorbate [81], [80].

2.2.3.8.2 Hysteresis

Hysteresis occurs when there is a difference between sorption and desorption [35]. As the equilibrium water content in a material depends not only on the R.H. of the ambient air but also on its temperature, the desorption isotherm will always lay above the adsorption isotherm at the same ambient temperature [80]. If there were a temperature difference, the higher temperature would result in a more accessible release of water molecules, causing the warmer isotherm to lay under the cold one [80].

It is crucial to study and understand Hysteresis, as its presence in the material might imply that capillary condensation has happened in the voids of the material during adsorption. This might have implications for the Thermal Conductivity and the moisture buffering capacity of the material, assuming that the condensed water will increase Thermal Conductivity and that moisture will not be released under normal ambient temperature during desorption [35].

Few theories were developed explaining the cause of Hysteresis in material [82]. These are gathered in detail in Latif, (2013) and are mentioned briefly here:

a) **The incomplete wetting theory**: Hysteresis occurs when there is a difference in the value of the contact angle between the liquid's surface and the capillary's walls.
b) **The Inkbottle theory:** according to this theory, Hysteresis accrues because of the bottleneck shape of the material's pores. Hysteresis happens when the pore geometry has a large body and small opening, causing slower moisture release than a geometry with a small body and large opening.
c) **The open-pore theory**: in the case of the material's pores being open at both ends, the meniscus formation is delayed during the adsorption causing Hysteresis.

2.2.3.8.3 Measuring Sorption Isotherm

Sorption Isotherm can be measured according to the British standard [83]. This standard specifies a method based on a climatic chamber, where the specimens are placed in a controlled temperature and relative humidity chamber. The Sorption Isotherm can be determined by periodical weightings of the test specimen (usually every 24h) until a constant mass is reached. While the temperature remains constant, the R.H. inside the chamber is either increased in steps (usually from 0%-95%) for the adsorption or decreased (from 95%-0%) for the desorption isotherm.

2.2.3.9 Water Absorption Coefficient

When the material comes into direct contact with liquid water, the surface of the materials will absorb the water by capillary action [35]. If the gravity effect is neglected, the movement of liquid water can be described by the Equation below [31]:

$$K = D_l \frac{\partial w}{\partial P_{suc}} \qquad (2.23)$$

Where: K= Coefficient of liquid water permeability (kg/m.s.pa), D_l= Diffusivity of liquid water (m²/s) and ∂P_{suc} = Capillary suction stress.

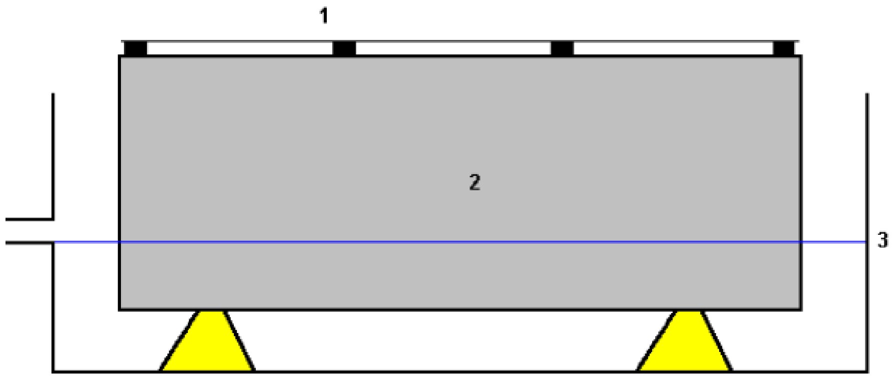
The absorption coefficient measures the "mass of water absorbed by a test specimen per face area and per square root of time" [84].

The water absorption coefficient is an important material property. Materials with a high water absorption coefficient can manage liquid water situations, such as driving rain, more effectively and hence can be more durable than materials with a low water absorption coefficient [85], [35].

2.2.3.9.1 Measuring Water Absorption Coefficient

The Water Absorption Coefficient can be measured according to the British standard [86]. The samples are placed in a water tank, resting on-point support so that the bottom of the specimen does not touch the surface of the tank (Figure 2-5).

The test duration is usually 24h, during which the specimen is weighted from the bigging of the test over specific time intervals as specified in the British standard [86].



Key

1 Grid to weigh down buoyant specimens (if required)
2 Specimen
3 Water level

Figure 2-5 Experiment Setup For Measuring Water Absorption Coefficient [87]

2.2.4 Common Construction Material of Libya

This subsection provides an overview of the common traditional and modern building materials used in Libya that will be further examined in this thesis. The hygrothermal properties of the selected construction materials are gathered from various sources, such as published research, manufacturers' construction websites, software databases (such as WUFI Plus and Design-Builder), and online building materials databases (such as the Online Materials Information Resource (MatWeb) [88], the National Institute of Standards and Technology (NIST) [89], and Materials Data Repository) [90].

While the aforementioned sources provide valuable information on the hygrothermal properties of construction materials, there is currently no direct information related to the key materials used in Libyan houses. Therefore, in chapter 4, this research will experimentally measure these properties for the Libyan context.

Table 2-5 presents some thermal and physical properties of selected building materials, and the experimental procedures for testing those properties, taken from published research. In contrast,

Table 2-6 at the end of this section presents the hygrothermal properties of the selected materials as found in online databases.

For the context of this research, the term "traditional" refers to materials used over many centuries, while "modern" refers to those specified for houses built using modern construction techniques. It is worth noting that some materials, such as limestone, can be both traditional and modern.

The reviewed materials include Clay (a traditional building material), Limestone (a traditional/modern building material), Hollow Concrete (a modern building material), Sandstone (a traditional/modern building material), Mud Block (a traditional building material), and Camel's Hair (a traditional building material). These materials were selected based on their common use in Libyan construction, and their hygrothermal properties will be further analysed in this thesis.

2.2.4.1 Clay

Clay is a natural material that, along with other materials such as wood and stone, has been traditionally used as construction material in many countries worldwide [91]. As a construction material, Clay is usually baked into bricks and roof tiles and, in many cases, is used as plaster material to cover mostly the interior sides of the envelope [6], [92].

Earth plaster has been used for years to cover exterior and interior surfaces [6]. However, it is argued that Clay plaster is more suitable for interior surfaces as it creates more comfortable and healthy spaces with a minimum environmental impact [93]. Furthermore, Clay plaster outperforms conventional industrial plaster, as the production of unbaked Clay and sand requires a small amount of energy compared to that needed to produce conventional plasters, such as lime or cement plaster, which require a very high temperature to process [93].

In the context of Libya, Clay is considered a traditional local building material and is available in most parts of the country. Therefore, the extraction and production of Clay will require a small amount of embodied energy and is a sustainable building material [6]. The hygrothermal performance of Clay remains unexplored in the context of Libya.

2.2.4.2 Sandstone

Sandstone is a natural stone that is locally available and traditionally used, especially in the mountain region of Libya [6]. Due to its strength and durability, Sandstone is usually used to construct walls of some traditional houses in Libya and could be used as a modern building material. There is a need to explore the hygrothermal properties of Libyan Sandstone, as there was no information found in the published research.

2.2.4.3 Limestone

Limestone is both a traditional and modern building material. It was traditionally used to construct houses in Libya [6]. Limestone is extracted from the coastal regions of Libya and is supplied to the rest of the country to be used for building construction. No available data regarding the hygrothermal properties of Libyan Limestone was found in the published research.

2.2.4.4 Hollow Concrete

A modern building material that is widely used in the walls of the contemporary houses of Libya. Rectangular-shaped blocks are made of cement, sand and aggregate. No available data regarding the hygrothermal properties of Libyan Hollow Concrete was found in the published literature.

2.2.4.5 Mud Blocks

Mud Block is a traditional building material used mainly in Libya's desert region. In addition to being natural, locally available, and cost-effective, Mud blocks can be considered eco-friendly and sustainable [12]. Earthen materials, such as Mud and Clay, claim to have better moisture performance than conventional building materials [12]. The relatively easy process of sourcing and producing Mud Block can lead to a site-to-service application, which can significantly reduce the costs of sourcing, production, and transportation. There is no available data regarding the hygrothermal properties of Mud blocks in the context of Libya.

2.2.4.6 Camel's Hair

Camel hair tents might be considered one of the oldest forms of houses in Libya, and despite being used as shelters for many years, the hygrothermal performance of Camel's hair was not found in the published research.

2.2.5 Thermal and Hygrothermal Values of Construction Materials

Table 2-5 below are the hygrothermal properties of some of the selected construction materials in the published research.

Table 2-5 Test Procedures and Hygrothermal Properties of the Selected Construction Materials as Found in Published Research

Material	Ref	Test procedure	Results	Notes
Limestone	[94]	***Thermal properties*** Thermal Conductivity, thermal Diffusivity, and specific heat capacity) were measured using ISOMET 2114, a Transient plane source device, and a surface prop IPS 1105. ***Sample Size:*** at least 60mm of flat surface diameter and a minimum thickness of 20mm. ***Number of samples*:** To overcome the non-homogeneity and anisotropy, 3 samples were tested, and 10 repeats for thermal conductivity measurement.	**Conductivity** (W/mK) = 0.70, **Specific heat** (kJ/kg K) = 0.82, **Bulk density** (m^2/g) = 1.71.	***Before testing:*** - All materials were cut to a uniform shape - The specimens were dried in an 80°C oven for a week, then left in a climate-controlled room at 20±2 °C and 50±2% RH - The results showed that Limestone has better thermal properties than the Sandstone
		Water vapour resistance (BS EN ISO 12572:2016) both dry cup and wet cup methods***.*** ***Water vapour sorption*** (BS EN ISP 12571:2013) climatic chamber method. - Three samples of each material were tested - For the dry cup, Silica gel was used to provide 0% RH - For the wet cup, potassium nitrate was used to provide 94% R.H. - All samples were left in a climate chamber at 23 °C and 50% RH until the constant mass was reached. - OHAUS scale (0.01g accuracy) was used to take the daily weightings.	**Wet cup** = 6.20 **Dry cup** = 13.99	- To investigate the appropriateness of the ISO 12571 for the selected climate (desert region of Egypt, where the peak temperature in summer was 38.8 °C and the max that can reach 44 °C), the full R.H. cycle (0-95%) was applied at 23 °C (as in ISO 12571) and 38 °C (as in the peak temperature) for the three materials. - To reflect the real R.H., each material was tested for 25-65% at 23 °C, 38 °C and 48 °C over 5 cycles. - Limestone has a lower capacity for moisture regulation compared to Sandstone
	[94]	***Moisture buffering value (MBV) using the standard NORD test*** - Due to their irregular shape, the stones were cut to provide the maximum surface area. - The samples were sealed with aluminium tape on 5 out of 6 faces - The samples were then exposed to 75% R.H. for 8 h and 33% R.H. for 16 h at 23 °C - A screen was placed around the mass balance to minimise the influence of air movement. - Anemometer was used to measure the wind speed, which was found to have an average of 0.1m/s - All samples were constantly weighted during the test.	**MBV**= 2.30 (g/m^2 RH%)	- All materials were cut to a uniform shape - The specimens were dried in an 80°C oven for a week, then left in a climate-controlled room at 20±2 °C and 50±2% RH

Sandstone	[94]	Thermal Conductivity, thermal Diffusivity, and specific heat capacity) were measured using ISOMET 2114, a Transient plane source device, and a surface prop IPS 1105. ***Sample Size:*** at least 60mm of flat surface diameter and a minimum thickness of 20mm. ***Number of samples*:** To overcome the non-homogeneity and anisotropy, 3 samples were tested, and 10 repeats for thermal conductivity measurement.	**Conductivity** (W/mK) = 1.11 **Specific heat capacity** (kJ/kg K) = 0.75 **Bulk density** (m^2/g) = 1.82	- All materials were cut to a uniform shape - The specimens were dried in an 80°C oven for a week, then left in a climate-controlled room at 20±2 °C and 50±2% RH
		Water vapour resistance (BS EN ISO 12572:2016) both dry cup and wet cup methods. ***Water vapour sorption*** (BS EN ISP 12571:2013) climatic chamber method. - Sample mass range 45-80 mg. - To ensure 0% moisture content, the specimens were dried in an oven at 105 °C until a constant mass - The specimens were held at 0% R.H. for 360 min at the set temperature.	**Wet cup** = 13.81 **Dry cup** = 22.81	- All materials were cut to a uniform shape - The specimens were dried in an 80°C oven for a week, then left in a climate-controlled room at 20±2 °C and 50±2% RH
		Vapour diffusion: cup method (NF EN ISO 12572) - Three samples were tested for each condition - The sample is sealed above the test cup that contains a salt solution. The test cup can be either a dry or wet cup - The whole system is then placed in a climate chamber, so the material was between two environments with different vapour partial pressure - A layer of air is presented inside the cup - The mass of the cup will vary (mass uptake with the dry cup and mass loss for the wet cup) due to the partial vapour pressure gradient between the inner part of the cup and the climate chamber	**Wet Cup** = 3-7. **Dry Cup** = 7-19	

Mud Block	[95].	***Adsorption-desorption isotherms*** using saturated salt solution method (GB/T 20312-2006) - All samples were oven-dried at 105 °C till constant mass was reached - Six relative humidities were used for the test and obtained using different salt solution - The samples were then placed in airtight containers containing the different salt solutions representing high and low humidities - The airtight containers were then placed inside a climate chamber at 20 °C and 60%RH - The samples were then periodically weighted until the weighting of two consecutive results 25=4h apart was less than 0.1% - Once the samples reached equilibrium at 97.3±0.3% R.H., they were transferred to lower R.H. to measure the desorption branch.		Earthen block reaches moisture equilibrium within 4 days The material has a large adsorption capability
	[96]	***Sorption–desorption isotherms using two methods: saturated salt solution and Dynamic Vapour Sorption*** - Specimen size 60x40x20mm³ - The specimen was dried to constant weight in a drying oven at 50°C - The saturated salt solution was used to produce five different RH%: 7%, 33%, 50%, 76%, and 97%. - The samples with the salt solution were placed in airtight boxes and placed in a controlled climate chamber at 21 °C - The samples were weighted periodically till the difference between two measurements 24h apart was less than 0.1% **Dynamic vapour sorption method:** - The samples were dried using dry N2 gas - Five samples (approx. 1x1x0.5cm) were placed on one side of the microbalance (DVS2) - The samples were measured at regular time intervals - The temperature was kept constant at 20 °C, and the R.H. changed in successive steps from 0-95%.		- Five earthen bricks were tested, and the results showed: - Earth bricks absorb a significant amount of water vapour, indicating their capacity to regulate the indoor R.H. - The results of the heat capacity confirm the data found in the literature - The dry thermal Conductivity, however, is much lower than those found in the literature (half the average value).

[97]	***Thermal conductivity (ISO/DIS 2008-2:2015)*** - Before the testing, the equipment was calibrated with an expanded polystyrene board - The specimens were oven-dried at 105 °C for 24h - Each measurement was repeated 3 times, and the mean value was reported.	**Conductivity** (W/mK) = 0.5228 to 0.9308	• Using hot disk apparatus (TPS-2500 S) The findings showed that the thermal Conductivity of the compressed earthen block linearly increases with increasing the bulk density
	Sorption–desorption isotherms using two methods: saturated salt solution and Dynamic Vapour Sorption- ***Method of saturated salt solution (NF EN ISO 12571):*** - Specimen size 60x40x20mm³ - The specimen was dried to constant weight in a drying oven at 50 °C - The saturated salt solution was used to produce five different RH%: 7%, 33%, 50%, 76%, and 97%. - The samples with the salt solution were placed in airtight boxes and placed in a controlled climate chamber at 21 °C - The samples were weighted periodically till the difference between two measurements 24h apart was less than 0.1% - Dynamic vapour sorption method: - The samples were dried using dry N2 gas - Five samples (approx. 1x1x0.5cm) were placed on one side of the microbalance (DVS2) - The samples were measured at regular time intervals - The temperature was kept constant at 20 °C, and the R.H. changed in successive steps from 0-95%		

Clay	[98]	***True Density, Thermal Conductivity*** - Sample preparation: - For thermal tests (UNI EN 1015-19), three specimens with surfaces of 15x15x4cm were prepared - For the water vapour permeability, three different cylindrical specimens, 15cm in diameter and 1 cm in thickness, were prepared.	**Ture density clay** (kg/m³) = 2859 **Ture density olive waste** (kg/m³) =1251 **Bulk density (clay + olive)** (kg/m³) = 1409-1669.	- Four different mixtures of Clay with olive waste - Properties vary according to the different mixtures: - Before the test, all specimens were oven-dried at 105C till constant mass - Adding olive fibres to the Clay resulted in a linear increase in its Porosity and a reduction in its density. - The addition of olive fibre also resulted in a reduction of thermal Conductivity, meaning better insulating properties - The mixture also showed a good moisture buffer capacity
	[98]	***Water vapour permeability using the cup method (UNI EN 101-19) And Moisture Buffering Value*** - Cylindrical shaped specimen - A saturated salt solution of Potassium Nitrate (KNO_3) was used for the wet cup test to provide 93.2% R.H. - For the dry cup test, a salt solution of Lithium Chloride ($LiCl$) was used to provide 12.4% R.H. - Each specimen was wax sealed on the top of a PVC vessel containing the salt solution - 1cm of the air layer between the water and the internal face of the specimen - The system was then placed in a climate chamber providing 20 °C and 50% RH - Mettler Toledo PB3002 balance, with an accuracy of ±0.01g, was used to weight the system till constant time variation of the mass was achieved	**Dry cup** = 22.1-25.0 **Wet cup** = 13.4-12.5	
		• ***Hygroscopic sorption properties (Sorption–desorption isotherms)*** • ***(UNI EN 12571:2013)*** - Three specimens were oven-dried at 105 °C for 48h - The specimens were then placed in a climate chamber with 20 °C and 30% RH		

		- The specimens were weighted till the weight loss between two successive measurements in the last 24h was less than 0.1% ***The salt solution in the desiccators;*** - At 97%RH, the salt solution in the desiccator was used to verify the moisture content - The samples were placed in a desiccator containing Potassium Sulphate salt solution - The desiccator was placed in a climate chamber at 20C - The sample was weighted daily till a constant equilibrium mass was reached.		
Hollow Concrete	[99]	***Bulk density and Thermal conductivity*** - Two 200 mm X 200 mm X 30 mm specimens were produced for each group totalling 18 specimens. - Thermal properties were determined According to the Chinese standard "Determination of steady-state thermal resistance and related properties–Heat flow meter apparatus GB/T 10295-2008."	**Bulk density** (kg/m^3) 1617- 2195. **Thermal conductivity** (W/m.K) 0.735-1.399.	- 9 material samples made of recycled waste material. - The thermal Conductivity increases with Increasing density
	[100]		**Bulk density** (kg/m^3) 2050. **Thermal conductivity** (W/m.K) 1.515. **Specific heat capacity** (kJ/kg K) 920.	Hollow concrete block filled with compressed straw bricks

Table 2-5 provides a summary of the hygrothermal properties of selected building materials, along with the corresponding test protocols for measuring those properties as reported in published literature. The table reveals that there is some variability in the values of these properties, which may be attributed to differences in the nature of the materials across different geographical locations or to variations in their composition. For instance, the clay and hollow concrete materials examined in the table were found to be mixed or filled with other substances such as straw or olive fibre. These discrepancies underscore the importance of conducting hygrothermal characterizations of building materials in the local and regional contexts to ensure accurate results.

Given the absence of relevant data on the key building materials used in Libyan construction, Chapter 4 of this thesis will focus on experimental measurement of their hygrothermal properties. The results of these experiments will be compared to the values presented in Table 2-5 and other published sources. By providing more detailed and location-specific data on the hygrothermal properties of Libyan building materials, this research aims to contribute to a better understanding of the performance of building envelopes in the region.

Table 2-6 Hygrothermal Properties of the Selected Construction Materials as Found in Online Material Databases

Material	Ref	Hygrothermal properties				
		Bulk Density (kg/m³)	Porosity (m³/ m³)	Heat Capacity (J/kgK)	Thermal Conductivity (W/mK)	Vapour Resistance (-)
Clay	[88]	1935	0.217	800	0.495	137.8
	[89]	1821	0.333	800	0.516	68.5
	[90]	1267	0.517	850	0.288	50
Sandstone	[88]	2268	0.14	828	2.503	87
	[89]	2224	0.17	771	1.684	73
	[90]	2300	0.05	850	2.3	70
Limestone	[88]	2500	0.05	840	0.7	770
	[89]	2440	0.12	850	2.25	140
	[90]	2650	0.035	2600	3	35.7
Hollow Concrete	[88]	2322	0.15	850	1.7	192
	[89]	2315	0.1296	800	0.733	182.3
	[90]	2300	0.18	850	1.6	197
Mud Block		1514	0.42	1000	0.59	11
Camel's Hair	-	-	-	-	-	-

The table presented above displays the hygrothermal properties of the selected construction materials collected from online material databases ([88], [89], [90]). As can be observed, there are variations in the values of the hygrothermal properties among the selected materials. These variations may be attributed to the distinct characteristics of the materials based on their geographic location or the differences in their composition, as in the case of Clay and Hollow Concrete, which were mixed or filled with other materials such as straw and olive fibre. The findings from the table highlight the significance of performing experimental categorization of materials whenever data is not readily available. In chapter 4 of this thesis, the hygrothermal properties of common building materials in Libya will be experimentally investigated to provide more accurate results representative of the local conditions.

2.3 Calibration and Simulation of Building Models

2.3.1 Introduction

In the study by Chong, Gu and Jia, (2021), building energy simulation is generally defined as a mathematical model that is used to assess the building's energy performance and user's thermal comfort under the influence of several input parameters, such as building geometry, internal loads, heating and cooling systems, occupancy, operational schedule, and weather conditions [102]. There is, however, increased concern regarding the credibility of simulation models within the building industry, as there is often a vast difference between the simulation results and the actual measured energy use once the building is operational, a mismatch known as "the performance gap" [103]. With new technologies being deployed, such as automated energy meter readings (AMR) and the internet of things (IoT), the performance gap is becoming more visible, with reports suggesting the gap between the measured and predicted data is as high as 2.5 times [104]. While it is reasonable to allow for some variation between the measured and simulated data, reports showed that, at present, the performance gap is too large to be ignored [105]. Therefore, reducing errors and minimising the performance gap is crucial.

Though calibration is not essential for building simulation research, its importance is increasing due to the level of credibility that calibration can bring to building models and building simulation research [106]. Reddy et al. (2007) defined the calibration process as: "the process of using a building simulation program for an existing building and tuning or calibrating the various inputs to the program so that predictions match closely with observed energy use". They added, "Historically, the calibration process has been an art form that inevitably relies on user knowledge, experience, statistical expertise, engineering judgment, and an abundance of trial and error. Unfortunately, despite widespread interest in the professional community, no consensus guidelines have been published on performing calibration using detailed simulation programs" [75], [102], [103], [104], [108], and [109].

2.3.2 Review of Calibration Protocols

Several international bodies, such as The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) [110], the Efficiency Valuation Organization (EVO) [111] and the Federal Energy Management Program (FEMP) [112], have set some criteria to evaluate the accuracy of the calibrated computer models and to determine when a model can be considered calibrated. Nevertheless, these criteria only focus on how well the calibrated model results match the measured utility data and do not describe a method to calibrate the model [108], [109].

Researchers have been spending much time and effort optimising the simulation and calibration activities. Most focus on simplified tools, requiring several parameter inputs to minimise the simulation time [113]. As mentioned earlier, several international bodies proposed guidelines for calibrating computer models. Table 2-7 below presents a compression between three main standards (ASHRAE, EVO and FEMP) regarding the calibration of building models.

Table 2-7 Comparison Between Calibration Guidelines Presented in EVO, ASHRAE and FEMP

<table>
<tr><th rowspan="2">Variable</th><th colspan="3">Standards</th></tr>
<tr><th>FEMP [112]</th><th>ASHRAE [110]</th><th>EVO [111]</th></tr>
<tr><td>Calibration steps</td><td>Five steps include:
1. "Data collection"
2. "Input data and test baseline model"
3. "Calibrate the baseline model".
4. "Create and refine the performance period model".
5. "Verify performance and calculate savings."</td><td>The suggested eight steps are:
1. Producing calibration plan (i.e., selecting simulation software and calibration intervals - monthly or hourly)
2. Data collection.
3. Data input and simulation run.
4. Comparing the simulation output to the measured data.
5. Refining the model to achieve acceptable calibration results (this includes making "logical" changes to the input)
6. Producing two models (Baseline and post-retrofit). Apart from the simulation results, the rest of the data (E.g., weather, occupancy etc.) must be uniform between the two models.
7. Energy savings are estimated by comparing the baseline and the post-retrofit model.
8. Report observations and energy savings (results, input data and weather files).</td><td>The calibration is achieved by running the simulation model under a set of conditions, as needed until the measure and simulated energy use are reasonably matched.
Following the collection of as much data as possible, the calibration process is as follows:
1. Assuming and documenting other input parameters.
2. Verifying that the simulation results predict a reasonable operating result, for example, zone temperature and humidity.
3. Comparing the simulated and measured energy data and assessing the patterns in the difference between the two sets of data.
4. Revising the assumed input in 1 and repeating steps 2 and 3 to bring the simulation results close to the monitored energy consumption.</td></tr>
<tr><td>Data collected</td><td>Data include:
- Utility bill (minimum 12 consecutive months)
- As-built drawings (i.e., architectural, mechanical, and electrical)
- Site survey data (Building audit- HVAC details, Lighting, Occupancy, Plug load, ventilation rates, Envelope details)
- Short-term monitoring of sub-systems performance
- Equipment spot measurements (E.g., lighting, HVAC etc.)
- Interviews with occupants/ operators of the building</td><td>Data include:
- Building surfaces dimensions and properties
- Utility data (hourly and monthly)
- HVAC details
- Operation and schedule
- Spot measurement of the HVAC system
- Weather data</td><td>Usually, 12 months of the utility bill.
Other data (to be measured at short intervals, e.g., day, week, or month) might be used. The data can include:
- Occupancy and operation
- Equipment type and operation
- Energy loads
- Ventilation and infiltration rates
- Lights</td></tr>
</table>

	- Site weather data for the simulation period.		
Calibration levels	Three levels of calibration: - Calibration on system-level, on hourly intervals - Calibration of the whole building at Monthly intervals - Calibration of the whole building at hourly intervals.		Energy use is calibrated with hourly or monthly utility bills or end-use metering.
Minimum requirements	**Simulation period:** - Monthly intervals - Minimum of 12 months (preferably 24,36 or 48). **Calculations in terms of:** - MBE (Mean bias error) where monthly MBE.month = ±5%, hourly MBE.month= ±10%. - Cv (Coefficient of performance) - RMSE (Root mean square error) where Monthly Cv (RMSE)month= ±15%, Hourly Cv (RMSE)month= 30%,	**Simulation period:** At a minimum, simulation results are to be compared with the monthly utility data and spot measurements. **Calculations of results:** - MBE (Mean bias error) where monthly MBE.month = ±5%, hourly MBE.month= ±10%. - Cv (Coefficient of performance) - RMSE (Root mean square error) where Monthly Cv (RMSE) month= ±15%, Hourly Cv (RMSE)month= 30%,	**Calculations of results:** - Hourly (MBE) = ±10% - Monthly (MBE) = ±20% - Hourly CV (RMSE) = ±20% - Monthly CV (RMSE) = ±1% to ±5%

- **Observations from Table 2-6**

Table 2-7 above compares three recognised calibration guidelines produced by three international bodies (ASHRAE, EVO and FEMP). From the comparison in Table 2-6, the following was observed:

a) The three standards suggested different approaches to calibrating building models. In general, however, there is an agreement between the three guidelines on the following aspects:

- Data collection
- Creating computer models and running simulation
- Comparing the measured and simulated energy data and rerunning the simulation (if needed, and as much as needed) to refine the calibration results.

These parameters (data collection, creating the models, and comparing data) are adopted in the proposed methodology for this research.

b) The suggested calibration guidelines are for calibrating the energy consumption of buildings. Only EVO guidelines included using indoor thermal conditions as a setback for the energy calibration.

The current research will not only calibrate the energy consumption but also the indoor hygrothermal conditions (indoor temperature and relative humidity).

c) The three guidelines highlighted the importance of using onsite representative weather data, if possible, as this is a critical step in enhancing the calibration results.

For the current study, an onsite weather station was installed in the Case Study Houses location to collect real weather data. Additionally, a temperature and relative humidity data loggers were mounted outside each Case Study. The collected weather data will be used for the calibration and simulation of the Case Study Houses.

d) It is agreed between the three guidelines that the minimum accepted calibration level is the monthly utility bill over 12 months. Hourly calibration is more accurate, though it can be highly time-consuming.

In this research, the Case Study Houses were calibrated over 12 months using annual weather and electricity consumption data, collected at sub-hourly intervals. For more accuracy, the three Case Studies were calibrated at hourly intervals.

e) Having more data during the data collection process is a critical factor in obtaining more accurate calibration results and can also significantly contribute to reducing the calibration time. In the case of some missing data, the missing data can then be reasonably assumed.

In the current research, as much as possible data was collected from monitoring the Case Studies, site visits and interviews with the occupants of the Case Study Houses. The missing weather data (rain and wind speed and direction) were obtained from a nearby weather station.

f) Ventilation and infiltration rates impact energy consumption and indoor hygrothermal conditions. Ventilation was not highlighted in ASHRAE and FEMP as a part of the data collection process.

2.3.3 Different Levels of Calibration

The level of calibration is determined by several factors, for instance, the project value and the availability of building data. At a minimum, all models should be calibrated at monthly intervals. [114]. In general, and for most computer models, different levels of calibration, such as the following, can be performed [115]:

- **Sub-system Level Calibration Using Hourly Data;** The simulated hourly energy consumption is compared against the measured hourly energy consumption for the monitored building sub-system. It should be noted that most simulation software, including Design-Builder, use values in a minimum 1-hour interval, which means that, for calibration, the monitored data might need to be averaged over each hour [115].
- **Calibration at the Whole Facility Level Using Monthly Utility Data;** This is the minimum calibration level, which compares the monthly utility bills with energy use projected by the simulation software.
- **Calibration at the Whole Facility Level Using Hourly Utility Data;** The measured data is compared against the simulation data at an hourly interval and for a period defined by the user (usually one month billing period). These values can be later calculated for the whole period or weekdays, weekends, and holidays separately.

In the current study, the building models of the Case Study Houses will be calibrated at hourly intervals, and the results will be presented as average monthly values.

2.3.4 Review of Published Calibration Methodologies

Clarke, Strachan and Pernot (1993) have proposed four main categories for model calibration: the graphical, mathematical, manual, and automated methods. Different methods can be individually utilised or combined from these main categories and used during the same calibration. For instance, graphical and mathematical methods can be combined during the calibration of a building model. Likewise, manual and automated calibrations can be based on analytical methods, [76], [117]. The proposed categories are listed below, with a brief description for each type:

- **Manual calibration:** is the most common category based on the user's experience and judgment, without a systematic or automated procedure. This method includes a "trial and error approach", which is fine-tuning input parameters based on the user's experience and knowledge about the building.

- **Graphical techniques:** the graphical technique includes a comprehensive graphical representation of the results, consisting of time series and scatter plots.
- **Calibration based on analytical procedures:** this method is based on analytical test procedures, such as long- or short-term monitoring (i.e., in situ measurement of U-value and audit reports). This category does not employ a statistical or mathematical calibration process.
- **Automated Techniques:** a technique which is based on Analytical and Mathematical Approaches. This category includes all approaches that are not user-driven and are built on a type of automated procedure.

The absence of an official universal calibration methodology remains a significant issue. Therefore, researchers and professionals have been spending substantial time and effort on a simplified calibration methodology. Table 2-8 below explores and analyses some calibration methodologies found in published research.

Table 2-8 Comparing Calibration Methodologies Found in Published Research

Ref	Proposed Methodology	Simulation tool	Error evaluation	Period	Notes
[118].	**Six steps methodology, consisting of:** **1.** Calibration of power and schedules of constant loads. **2.** Simulation of design days and thermal loads analysis; to define heat sources of the building that will undergo the sensitivity analysis. **3.** Sensitivity analysis; over input parameter related to significant heat gains/loss. **4.** Adjustment of input values with a high level of influence and uncertainty. **5.** Whole-year simulation; to define error ranges over time **6.** Final adjustments	Energy-Plus			The model is for a public office with an area of 26,274m². Energy consumption data was obtained from the electricity company. The study presented a method for defining heat sources in buildings (parameters that will undergo sensitivity analysis).
[109]	The study approach combines evidence-based model development with statistical Monte-Carlo-based optimisation techniques and is divided into the following steps: **1.** Data gathering/Building audit includes; Building Information Model (BIM), as-built drawings, Operation	**1.** Version control software track **2.** SketchUp **3.** Energy-Plus	**Electricity consumption** - Daily MBE=-9.37% - Daily CV(RMSE)= 54.68% **Heat energy consumption**	Two ten days periods in April and May	The methodology was applied to a 700m² naturally ventilated library. Both energy and zone temperature is calibrated.

	& Maintenance (O&M) manuals, surveys, and interviews **2.** Evidence-based Building energy simulation model development (creating the initial model, Applying parameter changes). **3.** Bounded Grid Search; Best guess estimate for all unknown variables based on the knowledge of the building and systems. Defining the range of variation for unknown input variables. Monte-Carlo simulation includes the Generation of a sample from each probability density function (pdf), Evaluation of the model for each element of the sample, and Result analysis. **4.** Refined Grid Search (Optional). **5.** Uncertainty Analysis; includes calculating NMBE%**,** CV (RMSE%, and GOF.		- Daily MBE=30.48% - Daily CV(RMSE)= 787.07% **Zone temperature** - Daily MBE=-6.87% - Daily CV(RMSE)= 325.78%		Error analysis and results are presented in daily intervals. This method is complicated and requires a significant amount of time and resources.
[119]	**1.** Creating an initial model through as-built information, U-value measurements, Full-year climate data, Occupancy schedule, Heating system properties **2.** Fifteen simulations run till the model is calibrated: Runs 02-06 indoor temperature calibration. Runs 08-12 integration and adjustment of calculated infiltration rates. Run 13 integration of assumed additional heat transfer. Run 14 final adjustments of infiltration rates and indoor temperature profile. Run 15 integration of monitored occupant present data. **3.** Comparison between the simulated and the monitored data in two ways; - Linear Correlation (hourly monitored and simulated data). - Error analysis: RMSE and MBE.	EDSL Tas		12- month	The calibrated variables include; - Simulation of hourly indoor temperature. - Simulation of monthly energy consumption. The author did not describe their methodology for calibrating the indoor temperature.
[120]	**1.** Development of baseline model **2.** Measurements of calibration variables include HVAC, Envelope: construction and layout. **3.** Simulation runs and adjustments of parameters.	The model was created in Open studio and then translated to Energy Plus.		Specific days: One-minute interval calibration	Data included: air temperature and end-use electricity consumption. Calibration using onsite weather data.

				data were available for 11 periods of 2 days each, spread over 9 months.	
[121]	**Two levels process:** **1.** Data collection includes Building data (plans, etc.), Weather data, occupancy and schedule, envelope details, HVAC details, as-built Plug load details, and lighting details. **2.** Implementation of the monitoring data includes: Heat pump electricity consumption, Boiler and pumps electricity consumption, Underfloor heating thermal energy released, Hot water temperature and flow rates, Heat produced by the thermal solar panels, HVAC electricity consumption, Survey, and interviews	Energy-Plus	Hourly MBE=5.6 % -7.5% Hourly CV(RMSE) = 7.3%-25.1%	One-year data at hourly intervals	The model is a three-storey research building with a 4500m² floor area. Version control software is used to track the history of calibration. The results include calibration of indoor temperature in hourly intervals.
[122]	A manual calibration method was used (trial and error approach).	Energy-Plus and Design-Builder	Monthly MBE= 4.8% for electricity and 4.0 % for gas. Monthly CV(RMSE)=5.9% for electricity and 5.0% for gas.	12-months.	The model is an Aquatic centre with an area of 10,839m². The model was constructed using Design-Builder and Energy-Plus to include the pool within the building and perform the simulation.
[123]	**Six steps methodology:** **1. Building the model;** Data collection (Architectural drawings, Plug load etc.)**,** Creating the model in SketchUp, exporting the model to SIMEB, Obtaining the weather file (online); modifying and adjusting data. **2. Analysing measured data sets;** Daily clustering analysis divides the measured period into six classes (Figure 1. in the paper). **3. Defining calibration periods;** Three periods of one week were selected, representing three modes of operation: hot, mild, and cold.	Energy-Plus, SketchUp and SIMEB	Hourly MBE=1.5%-4.2%, Hourly CV(RMSE)= 15.2%-24.1%		Five commercial buildings were calibrated. Electricity demands for one year on 15 minutes intervals

	4. Adjusting the model; Running the simulation, identifying errors and parameters, Adjusting the parameters **5. Setting up parametric runs** and running sensitivity analysis. **6. Setting up optimisation runs**, running simulations and changing the most influential parameters			
[124]	**Seven steps process:** **1. Base case modelling; (**hourly weather data, energy records, building drawings, Site visits and interviews, and short-term measurements). **2. Baseload analysis;** (monthly bill analysis, 1-day electricity consumption data, outdoor and indoor temperature analysis, breakdown of electricity usage by category. **3. Mid-season calibration;** One-month (April) electricity calibration. Parameter modification (occupancy, lighting equipment. Etc). Fine-tuning of occupancy uncertainty (weekend load variation. etc.). **4. Site interview and confirmation;** Checking operation to find reasons for significant discrepancy after step 3. **5. Heating and Cooling season calibration;** (HVAC system and system efficiency calibration). **6. Validation of the calibrated base model;** several checks were carried out, including checking monthly errors, critical discrepancy check using rang plot of historical energy records, comparison of baseload and usage patterns by category, Sensitivity, and uncertainty analysis.	DOE2.1E		- The model is a 26 stories commercial building. - Utility bills at monthly intervals. - By having this level of detail (energy consumption by category, detailed occupancy etc.), the author managed to calibrate and predict the annual consumption for the whole building by just calibrating one month.
[108]	An optimisation-based approach consists of four steps: **1. Simulation of base case model;** as-built data for creating the model; metrological data for creating the weather file; and other data such as indoor temperature and heating energy consumption. **2. Sensitivity analysis;** (values for the most influencing parameters related to the site, building envelope,	Energy-Plus and Gen-Opt	MBE=0.01%-0.83% CV(RMSE)= 0.19%-20.40%.	Two-storey test building with 162²m floor area. - Total of 11 simulation runs: 1-6 run varying time-related parameters (i.e., equipment, schedule, infiltration, etc.). Runs from 7-11, envelope-related

	operation and building system were gathered from the literature). **3. Optimization-based calibration;** running simulations and altering parameters to minimise error range. **4. Results validation;** in terms of Mean Bias Error (MBE), Root Mean Square Error (RMSE).			parameters (thickness, density, Conductivity, and specific Heat). - The time interval used to present the results is unclear (i.e., monthly, daily, hourly etc.).
[125]	**Six steps methodology:** **1."Gathering baseline information and proofing performance data,** including checking performance data indices (such as annual energy use per m^2) against benchmark energy use data to detect the gross error. Evaluating data quality using visual or statistical screening methods. Creating audit data forms **2."Define a heuristic static knowledge base of templates of the influential parameter inputs to the detailed simulation model";** isolating/separating influential and non-influential variables. Defining preferred or base-case input values for influential variables involves assigning minimum and maximum values. Developing DOE-2 consistent simulation input templates generic to a building type and HVAC system using audit information. **3."Use a blind coarse grid approach to sample the search space randomly";** Define "best guess" default values for non-influential variables that do not change during the calibration process using knowledge specific to the building. Discretise the probability distribution or variability of the continuous variables into strata or levels. Determine probability-weighted mid-point values for each section. Generate the necessary combinations or trials of the numerous influential input parameters. Identify promising subsets of parameter vector combinations based on goodness-of-fit criteria between simulated and actual monthly utility bill data over the year. Run DOE-2 simulation program in batch mode for as many trials as generated above. Perform sensitivity	DOE-2	Normalized Mean Bias Error (NMBE) and Coefficient of Variation (CV).	A very detailed methodology involving various calculations. These calculations might be complex, especially for inexperienced users. The author calibrated energy use only and not the indoor temperature. The methodology might be used to calibrate the indoor temperature

analysis using the above subset of promising trials to identify the subset of strong parameters from the list of influential input parameters. Perform replicate tests to obtain statistically robust results. 4. **"Refine the strong parameters' numerical values to improve the simulation outputs' prediction accuracy to the utility bill data as closely as possible".** 5. **"Identify plausible sets of solutions or plausible input parameter vectors".** 6. **"Compute uncertainty in calibrated model prediction";** the final step involves proposing a statistically sound approach, recommendations, and suggestions.	

Table 2-8 above reviewed different methods for calibrating building models. The reviewed studies vary in approach, simulation tool, calibration methodology, calibration period and building undergoing the calibration. There is an agreement, however, in terms of error evaluation, as most of the reviewed studies use MBE and CV(RMSE). In general, most of the methods are based on a trial-and-error approach. Nevertheless, the number of simulation runs can be significantly reduced by, first and most importantly, having as much data as possible (as in the case of Yoon, Lee and Claridge, (2003)) and second, by adopting innovative methods, such as sensitivity analysis (as in [77]). It was noted that the reviewed methods are used to calibrate the energy use of large-scale public buildings. This does not mean that similar methods cannot be used to calibrate the energy use and the indoor hygrothermal condition of small-size domestic buildings. The current study presents a calibration methodology adopted from the reviewed publications in table.2. and will be used to calibrate the models of three small domestic Case Studies in Libya. The adopted methodology is discussed in more detail in chapter .3. (Methodology) and the calibration results of the three Case Study Houses are presented in chapter 5.1.

2.4 Chapter Summary

This chapter provides the contextual research background for the thesis. The following conclusions are drawn:

- A review of the hygrothermal behavior of materials and building envelope was undertaken and showed that some hygrothermal material could be used to moderate indoor temperature and relative humidity. If well designed, the building envelope can play a significant role in providing hygrothermal comfort and reducing the energy consumption of buildings.
- The most important material properties related to heat and moisture movement and storage in building and building envelopes were determined from the review. They include; Moisture Buffer Value (MBV), Water Vapor Diffusion Resistance Factor (μ Value), Sorption Isotherm (u), Water Absorption Coefficient (Aw), Density (ρ), Porosity (φ), Thermal Conductivity (λ), Thermal Diffusivity (α), and Specific Heat Capacity (C_p).
- Construction materials from Libyan were reviewed, and the most common traditional and modern building materials were identified as being locally available, mostly naturally sourced, and potentially could contribute to improving hygrothermal comfort within the Libyan houses.
- This study conducted a review of published hygrothermal properties of various building materials. Although some data exists for certain materials, comprehensive data for the key materials used in construction in Libya is lacking. Furthermore, there is a dearth of information on the properties of Camel's Hair. This gap in knowledge is a significant limitation for the construction industry in Libya and underscores the critical need for further research in this area. Thus, this thesis aims to address these gaps by conducting experiments to determine the missing hygrothermal properties of selected construction materials. The results obtained will be compared with existing literature and online material databases such as MatWeb, NIST and Materials Data Repository and will be used in Chapter 5 of this research.
- This chapter also reviewed the methods and protocols for calibrating building models. A methodology for building model calibration was adopted from the review and is presented in chapter.3.

Chapter Three, Methodology

3 Methodology

3.1 Introduction

This chapter provides an overview of the methodologies and tools used for the data collection for this research. It includes an outline of the methods, criteria for selecting and monitoring the Case Study Houses, a description of the tools used for data collection, criteria for selecting and testing the construction material samples, a description of the chosen hygrothermal performance simulation tools, and the methodologies for the calibration and simulation of the Case Study models.

The following definitions are used in this chapter:

- **Research Methodology**: A research methodology is usually described as a systematic approach to tackling an issue and is the science of how the research will be carried out [126]. Moreover, a research methodology can also be defined as "the study of methods by which knowledge is gained. It aims to give the work plan of research" [127]. Research methodologies are broadly classified as qualitative and quantitative.
- **Research Methods:** Research methods are the techniques used for data collection, and they include, for example, experiments, field studies, and numerical modelling [127].

In summary, it can be said that research methods aim at finding a solution to a research problem, while research methodology aim is to apply the correct method to find the answer [127].

In line with the above definitions, the primary methodology for this research is mainly quantitative.

3.2 Outline of the Research Methods

This study investigates how traditional and modern building materials might be used or combined to improve hygrothermal comfort in Libyan domestic buildings. Thus, the aim will be achieved by applying a methodology that combines Case Study monitoring, laboratory experiments, and numerical simulations. Moreover, through the following compensation of methods (Figure 3-1),

a) **Hygrothermal Performance and Energy Consumption Monitoring of Case Study Houses** (Objective-3): three Case Study Houses were selected and monitored for their electricity consumption and indoor and outdoor thermal conditions. The data collected from monitoring the Case Study Houses will be used mainly to construct computer models in simulation tools to study the impact of changing the wall materials on the energy and thermal performance of the Case Study Houses.

b) **Laboratory-Based Experiments of Hygrothermal Properties of Selected Construction Materials Samples** (Objective-1)**;** Libya's most common construction materials were selected to determine their hygrothermal properties experimentally. The established material properties from the laboratory experiments will be used as a database for the simulation tools (step-c).

c) **Numerical Simulations of Computer Models in Design-Builder and WUFI Plus** (Objective-2 and 3)**:** in this step, simulations of the Case Study Houses in the simulation tools will be conducted to investigate what impact changing the wall materials might have on the energy and hygrothermal performance of the Case Study Houses.

The selected methods are explained in more detail in the following sub-sections.

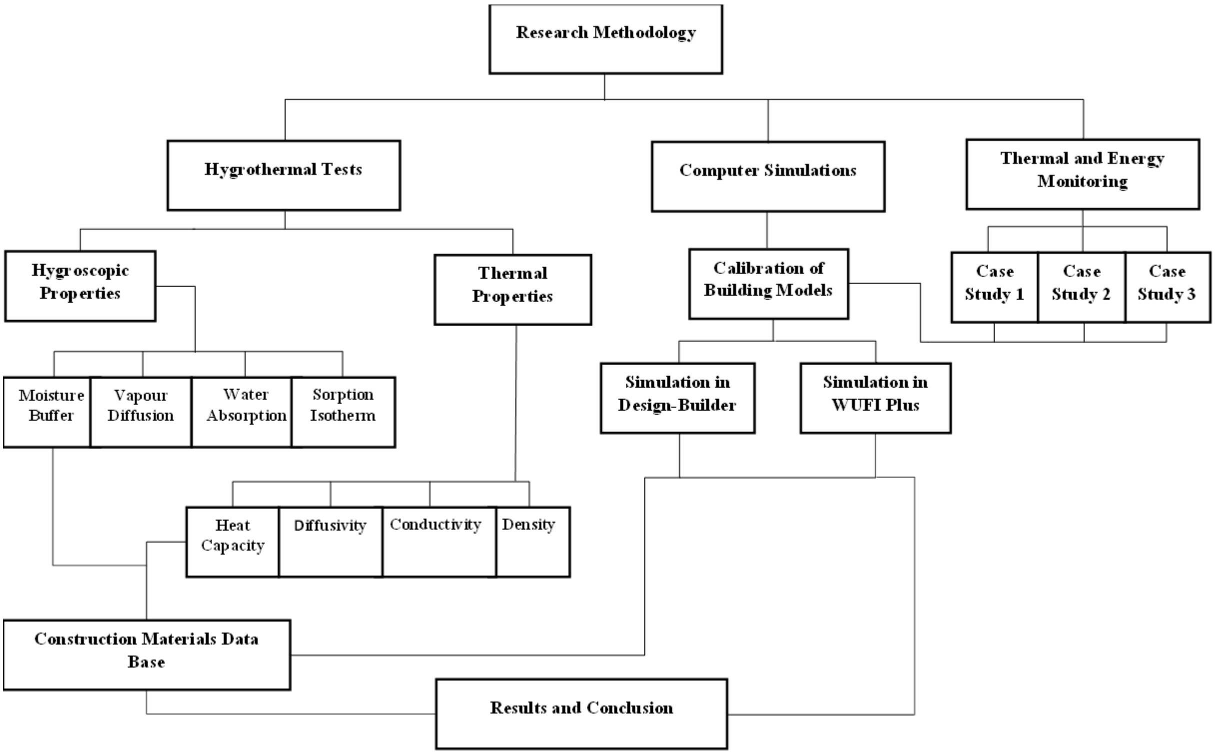


Figure 3-1 Outline of the Research Methodology

3.3 Preparation of the Test Specimens

The materials utilized in this study were obtained to represent common construction materials in Libya, including both traditional and modern varieties. It is important to note, however, that the sample size was limited, and as such, all materials were tested in their original forms as used in construction, including Camel's hair (refer to Fig. 3-5). As has been established, insulation materials function through the trapping of air within their structure, thereby reducing heat conduction [128]. For Camel's hair insulation to be most effective, it must be broken down and rendered fluffier to allow for increased air trapping. Due to the limited number of Camel's hair specimens available, it was only possible to test the material in its original form (see Fig. 3-5). A similar issue arose with the Hollow Concrete samples, which were tested only in their solid form without including the hollow section (see Fig. 3-5). However, the simulation process accounted for this by adding an air gap with the same dimensions as the material.

The first step in preparing the construction material samples was to cut the materials to the required sizes by the standards of each test. All materials were cut to a minimum size of 100mmX100mm, and thickness representative of the actual thickness.

After cutting the materials, the samples were stored at room ambient conditions (approximately 20°C and 50% RH) for over three months.

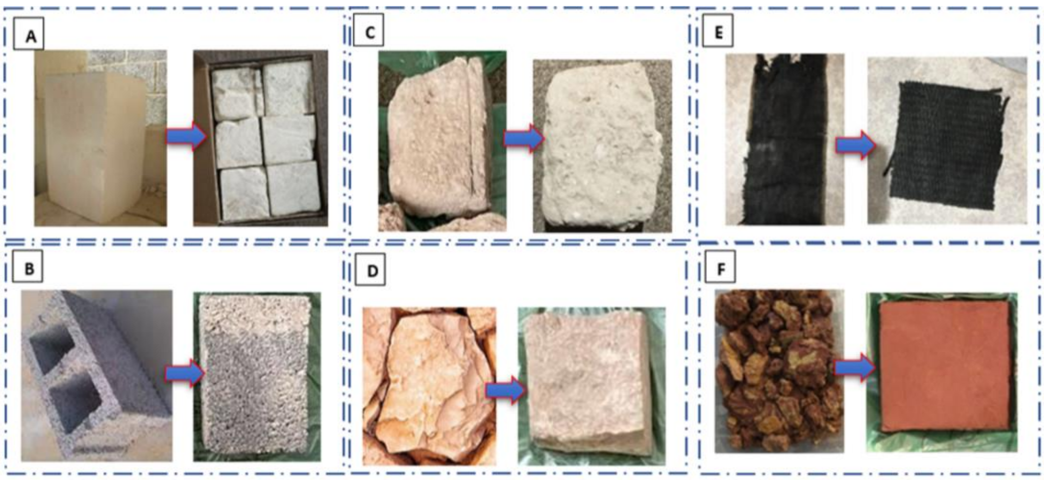
Libyan Mud Blocks, also known as Mud Bricks, are made of a mixture of Mud, Clay, and other materials such as straw, sand, or animal dung. The Mud Block mixture is typically formed into rectangular blocks and then left to dry in the sun before being used in construction [129]. The Mud Block samples were taken from an actual existed Mud Block structure.

Preparing the raw Clay and the Camel's hair required an extra effort as these materials were more difficult to define than the remaining materials. For the raw Clay, the material was first soaked in water overnight before it was moulded into square shapes with the required dimensions. The Camel's hair samples were also cut into square shapes with the required dimensions (generally 100X100 mm), and to provide a sufficient thickness to the Camel's hair samples, three layers of the product were placed on top of each other, each with an approximate thickness of 3 mm and the final product with a thickness of 10 mm.

The prepared materials are detailed below in Table 3-6 and Figure 3-5.

Table 3-1 Test Specimens' Details

Material	Used for	Original dimension (mm)	Sample's Dimension (mm)
Limestone	Wall	400X200X200 or 400X200X300	100X100X100
Hollow concrete	Wall	400X200X200	100X100X30
Mud blocks	Wall	300X100X200	100X100X 100
Sandstone	Wall	100X100X100 (approx.)	100X100X50
Clay	Plaster	25	100X100X30
Camel hair	Insulation	10	100X100X30



A= Limestone, B= Hollow Concrete, C= Mud Blocks, D Sandstone, E= Camel's hair, F= Clay.

Figure 3-2 Construction Materials Samples Before and After Preparation

3.4 Hygrothermal and Energy Performance Monitoring of the Case Study Houses

The first method applied in this research was the hygrothermal and energy performance monitoring of Case Studies. For this purpose, three representative Case Study Houses in Libya were selected to monitor their hygrothermal and electricity consumption performance (see the appendices for the ethics application approval from Cardiff University) . In addition to monitoring the hygrothermal and energy performance, a weather station was installed on-site to collect the annual weather data. The weather data was used to create weather files for the building performance simulations in Design-Builder and WUFI Plus. The collected hygrothermal and electricity consumption data was used to calibrate the Case Study computer models.

3.4.1 Description of the Case Study Houses.

Due to a lack of official documentation of housing stock in Libya, the Case Study Houses were selected based on the author's personal experience and judgment. Due to the limitations of time and resources, monitoring of the Libyan house was limited to only three representative Case Studies. As mentioned before, the majority of Libyan population occupies the North African Coast, therefore, the selected Case Study Houses are located on the Costal area where the majority of population and houses are located (see Fig 1-2).

- ❖ **Monitoring period;** Indoor and outdoor Temperature and relative humidity data loggers were installed in each of the Case study Houses. Electricity consumption data loggers were also used to monitor the annual electricity consumption of the Case Study Houses (at sub-hourly intervals). Additionally, a weather station was installed on site to collect the weather data (see3.3.3). The monitoring period is 12 months for each of the Case studies.

The Case Study Houses were selected based on the following criteria;

- ❖ **Type, Design and Layout;** The selected Case Studies represent Libya's most common house type, the detached house [4]. In general, the three Case Studies consist of living space, sleeping space and guests' space, usually separated from the rest of the house.
- ❖ **Floor area;** the three Case Studies are representative of the typical houses of Libya. The three Case Studies are single-storey house with floor areas of 95 ^{2}m, 85 ^{2}m, and 140 ^{2}m for the Case Study House 1, 2 and 3 respectively (see Table 3-1 for more details).
- ❖ **Orientation and surroundings**; the three Case Studies are detached houses and are North oriented (see Table 3-1).
- ❖ **Envelope Details:** The dominant construction materials for walls of modern Libyan houses are Hollow Concrete with Cement mortar, followed by Limestone and Cement mortar. Therefore, the walls of the Case Study Houses had to be made of those two materials. Roofs are mostly

flat and made of reinforced concrete. Outward openings with single-glazed windows are common in Libyan houses [130].

- ❖ **Occupancy:** The occupants of the Case Study houses had to be Libyan families to represent the typical lifestyle and occupancy behaviour patterns of the Libyan households. The number of occupants is representative of the average Libyan household (5 people) [4].
- ❖ **Equipment;** Mainly, houses in Libya depend on mechanical equipment for heating and cooling [130]. Along with the construction materials criteria and for comparison reasons, two houses use heating and cooling equipment. The last house is a free-running house with no heating or cooling devices.

Other limitations, such as accessibility to the houses with consideration to the family privacy, were also considered when selecting the Case Studies. Table.3.1. shows a comparison between the three Case Studies.

Table 3-2 Comparison Between the Three Case Study Houses

Criteria	Case Study-1	Case Study-2	Case Study-3
Type, Design, and Layout	Detached house, consisting of living, sleeping and guests space	Detached house, consisting of living, sleeping and guests space	Detached house, consisting of living, sleeping and guests space
Floor area (^{2}m)	95	83	140
Orientation	North	North	North
Envelope	Wall: Limestone, cement mortar Roof: reinforced concrete Openings: one main door, multiple outward-looking, single-glazed windows	Wall: Hollow Concrete, cement mortar Roof: reinforced concrete Openings: one main door, multiple outward-looking, single-glazed windows	Wall: Limestone, cement mortar Roof: reinforced concrete Openings: one main door, multiple outward-looking, single-glazed windows
Occupancy	Libyan family consisting of five people	Libyan family composed of five people	Libyan family consisting of five people
Equipment	Mechanically equipped for heating and cooling.	Mechanically equipped for heating and cooling	Free running with no heating or cooling devices

3.4.2 Description of Monitoring Tools

This sub-section describes the sensors and tools used for monitoring the Case Study Houses.

- ❖ **Indoor Temperature and Relative Humidity;** "Tiny-tag Ultra 2 Data Logger Temperature/Humidity" data loggers were used. The specifications of the data loggers used are shown in Table 3-2 below.

Table 3-3 Indoor Data Logger and its Specifications [131]

Specifications	
Memory size	32K (Non-volatile)
Readings	32000 (approx.)
Reading Types	Actual, Minimum, Maximum
Logging Interval	1 second to 10 days
Battery Life	Up to 12 months
Temperature Reading Resolution	0.01°C or better
Temperature Reading Range	-25°C to +85°C
Temperature Response Time	20 mins to 90% FSD in moving air
Humidity Reading Resolution	±3.0% RH at 25°C
Humidity Reading Range	0% to 95% RH
Humidity Response Time	10 seconds to 90% FSD

- **Outdoor Temperature and Relative Humidity;** "Tiny-tag Plus 2 Dual Channel Temperature/Relative Humidity TGP-4500" was used. The specifications of the used data logger are shown in Table 3-3 below.

Table 3-4 Outdoor Data Logger and its Specifications [131]

Specifications	
Memory size	32K (Non-volatile)
Readings	32000 (approx.)
Reading Types	Actual, Minimum, Maximum
Logging Interval	1 second to 10 days
Battery Life	Up to 12 months
Temperature Reading Resolution	0.01°C or better
Temperature Reading Range	-25°C to +85°C
Temperature Response Time	25 mins to 90% FSD in moving air
Humidity Reading Resolution	±3.0% RH at 25°C
Humidity Reading Range	0% to 100% RH
Humidity Response Time	40 seconds to 90% FSD (current data loggers, from SN 613165)

- **Electricity Consumption;** "Tiny-Tag View 2 Current Logger TV-4810" were used to monitor the electricity consumption of the Case Study Houses. The specifications of the data logger are shown in Table 3-4 below.

Table 3-5 Electricity Data Logger and its Specifications [131]

Specifications	
Total Reading Capacity	30,000 readings
Reading Types	Actual, Minimum, Maximum
Logging Interval	1 second to 10 days
Battery Life	Up to 12 months
Reading Range	0.15 to 200A AC
Frequency Range	40Hz to 10kHz
Maximum Current	240A AC*
Reading Resolution	10mA
Display Resolution	0.1A
Accuracy	0.5A to 10A (5% of reading +/-0.5A) 10A to 40A (3% of reading +/-0.5A) 40A to 200A (2% of reading +/-0.5A

3.4.3 Location and Placement of the Sensors

The three Case Study Houses are located in the Coastal region of Libya and are approximately between 2-4 km apart. This study will be using a physical science methodology for monitoring the temperature and relative humidity of the three Case Studies [132], [133].

To ensure accurate monitoring results, the sensors were placed in representative locations around the Case study Houses (such as the living areas and bedrooms, see Fig 3-2, 3-3 and 3-4). The temperature and relative humidity sensors were calibrated at Cardiff University prior to monitoring. Both external and internal sensors were protected from the effect of any external factors that might impact the results, such as direct sunlight, drafts, and any other sources of heat or moisture.

The weather station was installed outside Case Study House 1 (as it is approximately in the middle between the two Case Studies- around 2 km from Case Study House 2 and 3.5 km from Case Study House 3). Additionally, the external temperature and relative humidity data loggers were installed outside each Case Study.

The internal and external data loggers measured the sub-hourly indoor and outdoor temperature an relative humidity. The weather station measured the site temperature and relative humidity in addition to solar radiation. Other data, such as the wind speed and direction, and rain data were obtained from a local weather station. The monitoring period for the three Case Studies is 12 months in sub-hourly intervals.

The locations of the external and internal temperature and relative humidity sensors were chosen according to the British standard BS EN ISO 9869, 2018 [134], which recommends:

- Sensors shall be mounted according to the purpose of the test.
- Sensors shall be mounted in a way that ensures the results are representative of the whole building.
- It is recommended to install several sensors to obtain a representative average.
- Sensors shall be placed away from error sources, such as thermal bridges and cracks.
- Sensors shall be placed away from the influence of heating and cooling devices and fans.
- Outside sensors shall be protected from (snow), rain, and direct solar radiation.
- Sensors may be placed around the centre of the measuring element to obtain more representative results.

Figures 3-2, 3-3 and 3-4 show the Layout of the three Case Studies and the sensors’ locations within the houses.

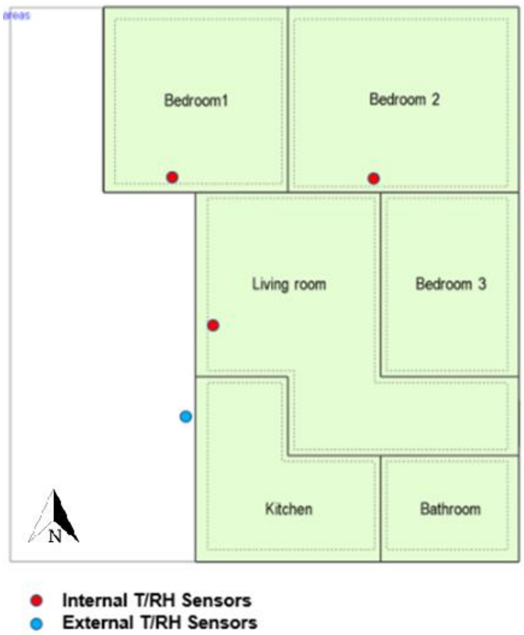


Figure 3-3 Layout of Case Study House 1

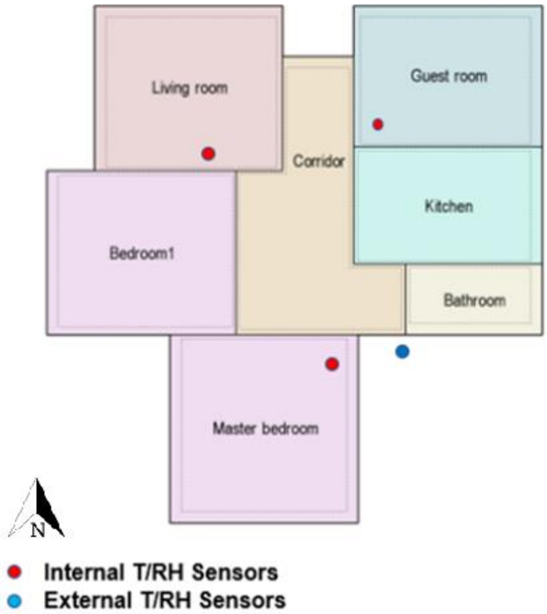


Figure 3-4 Layout of Case Study House 2

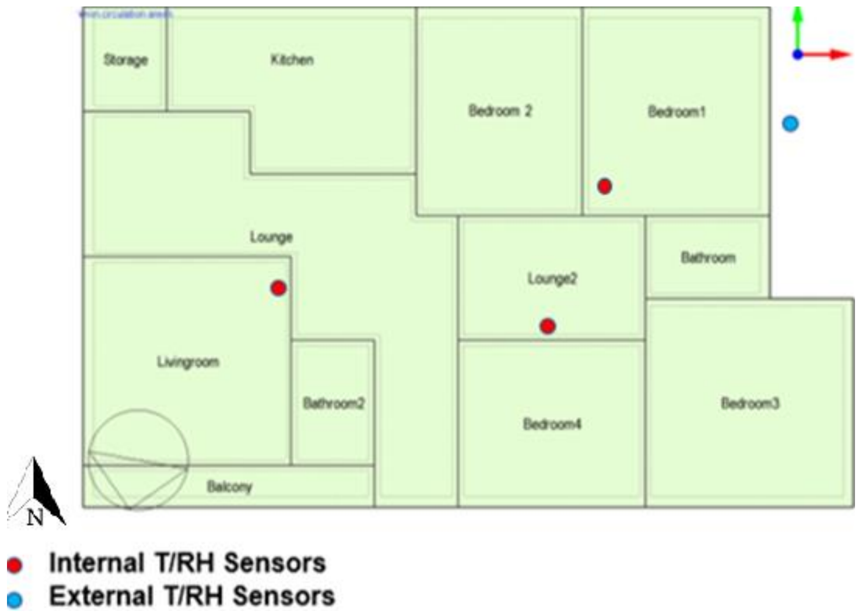


Figure 3-5 Layout of Case Study House 3

3.5 Determination of Hygrothermal Properties of Selected Construction Materials Samples

Construction material samples representing Libya's common traditional and modern building materials were collected and prepared to be tested for their hygrothermal properties. Table 3-5 below are the selected construction materials and their use in buildings.

Table 3-6 Selection of Construction Materials and Their Use in Buildings

Traditional Material		Modern Material	
Mud Block	a traditional material used mainly in the desert region (see Fig 1-2), which is about 90% of the total area of Libya. They consist of a Sun-dried mix of mud	**Limestone**	Limestone is Traditional material that is still used in modern houses. Limestone is a common wall material, traditionally used in the Coastal

	(about 70%) and hay (about 30%), and dimensions of about 25cm*25cm*50cm		region and is still used in modern houses in all the regions of Libya (see Fig 1-2). The dimensions are 20*20*40cm and 20*30*40cm.
Sandstone	Primarily used in the mountain region (see Fig 1-2) and is used for walls.	**Hollow Concrete**	Hollow Concrete block is the most common construction material and is used in all the regions of Libya (see Fig 1-2).
Camel's hair	Tents are one of the oldest house forms, common in Libya and Middle Eastern countries. No studies concerning the tents or the use of Camel's hair in construction were found.		
Clay	Clay is a widespread construction material that is used traditionally around the world.		

3.5.1 Material Testing Methodologies

Moisture movement within hygroscopic building materials combines liquid and vapour flow and depends on the material's temperature, humidity, and properties [87]. Three phases of moisture movement within hygroscopic materials can be defined:

- At very low humidifies, moisture transport is through vapour diffusion alone. The permeability can be derived from the dry cup test as in the British standard BS EN ISO 15272 [135].
- At higher humidity (up to 95%), the pores are filled with a mixture of gas and water with a simultaneous flow of vapour and liquid.
- At humidity above 95%, and depending on the material, the total mass transport is dependent on the liquid phase.

Understanding heat and moisture transfer and distribution through buildings and building materials are critical in evaluating thermal comfort, thermal movement, energy use, and avoiding potential moisture problems. In line with the above and section 2.3., the following hygrothermal properties are experimentally investigated:

3.5.1.1 Moisture Buffer Value (MBV), (g/m^2 RH%)

MBV defines the ability of a material to exchange moisture with the indoor environment. Furthermore, MBV measures how much moisture can be absorbed or released when the humidity surrounding the material changes [60]. Therefore, the objective of the MBV test will be to evaluate the MBV of building materials exposed to indoor air. The basic principle for measuring the MBV is exposing the partly sealed test specimen to a cycle change in the ambient relative humidity. Because of the difference in the RH, the specimen will gain or lose weight. This weight change over a certain time can be considered an expression of the MBV of the test specimen.

3.5.1.1.1 Methodology

The Moisture Buffering test was carried out according to the NORDTEST protocol [136], (see 2.2.3.6.3 for more details).

Three representative samples of each material were tested. The test principle is based on a climatic chamber, where the test specimen is exposed to a cycle of relative humidity. Each cycle combines 16 hours of exposure to 75±3% RH followed by 8 hours to 33±3% RH representing the low and high relative humidity, while the temperature is kept constant at 23±0.5°C during the test. The test chamber's relative humidity is maintained using a saturated salt solution. Details of the salt solutions used and the preparation of the saturated salt solutions can be found in Table 3-7 below.

Table 3-7 Preparation of Saturated Salt Solution for the MBV Test [137]

Salt	RH% at 23°C	Exposure time (h)	Water of crystallisation	Solubility	
				At a temperature of water (°C)	g per 100 ml of distilled water
Sodium chloride (NaCl)	75.36±0.13	8		0	35,7
				100	39,12
Magnesium Chloride (MgCl2)	32.92±0.17	16	0·H2O	20	54,25
			0·H2O	100	72,7
			6·H2O	20	167
			6·H2O	100	367

The required salt to produce the saturated solution is mixed with distilled water and then heated to the given temperature till the excess salt is just dissolved in the water. The mixture is then cooled slowly to room temperature while stirring continuously.

3.5.1.1.2 Equipment

For the MBV test, the NORDTEST protocol requires the following:

- **Saturated Salt Solutions:** Saturated salt solutions were used to provide the relative humidity levels required by the test protocol. (See Table 3-7 above).
- **Climatic Chamber:** Two airtight plastic boxes provided the required climate conditions. The first box provided the low RH (33%) using MgCl2 solution, and in the other box, NaCl solution was used to give the high RH (75%) (Table 3-7).
- **Glass Tray:** two glass trays containing the different saturated salt solutions were placed inside each box. in top of each glass tray, a stainless-steel rack was placed to act as a specimen holder.
- **Wireless Temperature and Relative Humidity Sensors:** two data loggers with time intervals of two minutes were placed inside the climate chambers to monitor the temperature and relative humidity levels during the experiment.
- **Analytical Balance:** a high-accuracy analytical balance with a resolution of 0,01g was used to measure the change in the test specimen's mass during the humidity cycles.
- **Fan:** two small fans were used for each box to provide air velocity between 0.05 and 0.15 m/s as required by the NORDTEST protocol.

The detailed experiment setup is as in Figure 3-6 below.

3.5.1.1.3 Test Procedure

Following the NORDTEST protocol, the test specimens were sealed using aluminium tape covering all sides except one side. The test specimens were placed inside the box with the high RH (75%) for eight hours before moving to the second box with the low RH (33%) for sixteen hours. At the end of each exposure, the mass change of the samples was measured.

The MBV was then calculated as mass change (Δm), per area (m^2), and per change in the relative humidity (ΔRH). The change in the specimen's mass (Δm) was then calculated as the average weight gain during the moisture uptake (75%RH) and average weight loss during the moisture release (33%RH) per cycle. The experiment continued until there was no more than a 5% variation in 3 consecutive determinations of Δm.

The MBV test results can be found in section 4.2.1. of chapter 4.

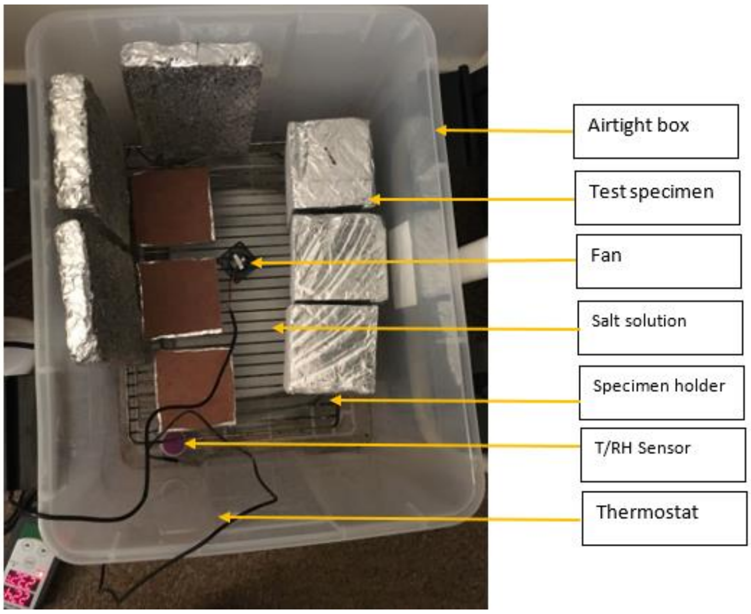


Figure 3-6 Experiment Setup for the Moisture Buffer Value (MBV)

3.5.1.2 Water Vapor Diffusion Resistance Factor (μ Value), (-)

The basic principle of this test is to seal the test specimen to an open side of a test cup that contains either a desiccant, for the dry cup or a saturated salt solution, for the wet cup. The assembly is then placed in a controlled climate chamber. Because of the difference in the partial vapour pressure between the test cup and the climate chamber, vapour flow through the specimen. The water vapour flow rate can be determined by periodic assembly weighing.

3.5.1.2.1 Methodology

The water vapour permeability is determined according to the British standard BS EN ISO 15272 [135] (see 2.2.3.7 for more details).

Three test specimens with a minimum area of 100mm² were tested. After measuring the specimen's thickness, the test specimens were sealed to the open side of a test cup containing desiccants or saturated salt solution, depending on the test type (Dry Cup or Wet Cup). The whole assembly is then placed inside a climate chamber. The minimum depth of the desiccants or the salt solution inside the test cup is 15mm, and the air space between the desiccants or the salt solution and the test specimen is 15±5 mm.

Due to the differential partial vapour pressure between the test assembly and the climate chamber, vapour flows through the test specimen. The water vapour flow rate is determined by weighting the test assembly every 24h until five successive determinations of change in mass per unit time for each specimen is ± 5% of the mean value.

3.5.1.2.2 Equipment

For this test, the following equipment has been used:

- **Test Cup;** made of glass, with shapes and dimensions corresponding to the test specimens.
- **Analytical Balance;** capable of weighting the test assembly to an accuracy of 0,01g.
- **Measuring Instruments;** capable of measuring the thickness to the nearest 0,2mm.
- **Climate Chamber;** capable of maintaining the temperature and relative humidity set points. In this case, two airtight boxes will be used.
- **Data Loggers;** to constantly record temperature, relative humidity, and barometric pressure.
- **Sealant;** that does not affect by the test conditions and does not cause any changes to the test specimen.

3.5.1.2.3 Test Process

Five test specimens of each material with dimension and thickness, as shown in Table 5.5. below were conditioned at 23°C ± 2 and 50% ± 5 RH for at least six hours to reach the constant mass. Depending on the test type (Dry Cup or Wet Cup), a layer of salt solutions with a minimum thickness of 15mm was placed inside each test dish. The test specimens were then placed and sealed on the top of the test dishes containing the salt solution so that one side is facing the test dish with the desired RH (0% RH for the dry cup and 93% for the wet cup) and the other side is exposed to the conditions of the test chamber (50% ± 3 RH). The test assemblies are then conditioned inside the climate chamber for 1-24h. Details of the salt solutions used and the preparation of the saturated salt solution as in Table 3-8 below, and Figure 3-7 shows an example of the test assembly.

The moisture flows through the test specimen due to the difference in the RH% between the test dish and the climate chamber. The test assembly is weighted every 24h until five successive determinations of change in mass per unit time for each specimen is ± 5% of the mean value.

Table 3-8 Preparation of Saturated Salt Solutions for the μ Value Test (BS EN 12085 and ISO 12572)

Salt	RH% at 23°C	Water of crystallisation	Solubility	
			At a temperature of water (°C)	g per 100 ml of distilled water
Calcium chloride (CaCl2)	0%			
Sodium bromide (NaBr)	57%	0·H2O	50	116
		0·H2O	100	121
		2·H2O	0	79,5
		2·H2O	81	118,6
Potassium nitrate (KNO3)	93%		0	13.3
			100	247

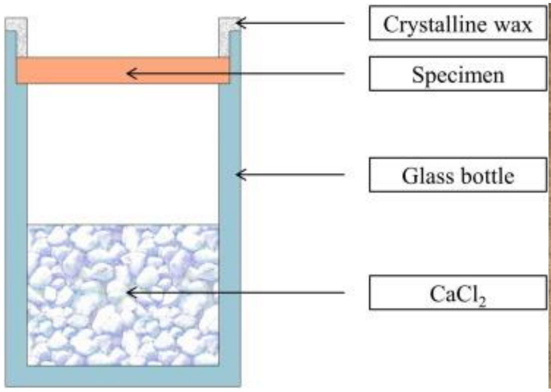


Figure 3-7 Test Assembly(Left) For Water Vapour Diffusion Resistance Factor Measurement [138]**. (Right) The Test Assembly During Mass Change Measurement (Clay Sample).**

3.5.1.2.4 Calculations

To calculate the change rate in the mass:

$$G_{1,2,}\frac{(m_2-m_1)}{(t_2-t_1)} \qquad (3.1)$$

Where:

m_1= mass of the test assembly at a time t_1(mg), m_2= mass of the test assembly at a time t_2(mg), $t_1$and t_2= successive times of weighting (hour), G= is the mean of five successive determinations of $G_{1,2}$ (mg/h) where G1,2 is within ± 5% of G.

To calculate the vapour diffusion resistance factor (μ):

$$\mu = \frac{\delta_\alpha}{\delta} \qquad (3.2)$$

where:

δ_α= water permeability in air, δ= Vapour permeability of porous system in the material.

To calculate vapour permeability (δ):

$$\delta = W.d \qquad (3.3)$$

Where:

W= Water vapour presence (mg/m²h Pa), d= thickness of the test specimen in (m)

to determine the Water vapour presence (W):

$$W = \frac{G}{(A.\Delta p)} \qquad (3.4)$$

Where:

A= surface area of the specimen (m²), Δp= pressure difference (Pa).

For the vapour diffusion equivalent air-layer thickness (Sd Value)

$$S_d = \mu.d \qquad (3.5)$$

Where; d is the thickness of the spacemen.

3.5.1.3 Sorption Isotherm (u), (Kg/Kg)

The objective of a Sorption Isotherm test is to determine the equilibrium relationship between the moisture content of a material and the relative humidity (RH) of the surrounding environment at a constant temperature. The British standard BS EN ISO 12571 [137] specifies two methods for determining the hygroscopic sorption properties of construction materials and products (see 2.2.3.8 for more details). In this study, the climate chamber method is used to determine the moisture content of the test specimens. The basic principle for the sorption isotherm test is the sorption curve, where the test specimen is placed in a series of test environments with relative humidity increasing in stages. For the desorption curve, the process is repeated in reverse order. The sorption and desorption curves can then be drawn.

3.5.1.3.1 Methodology

The Sorption Isotherm is determined by the climatic chamber method according to the British standard [137]. A minimum of three samples, with dimensions of 100X100 mm and actual thickness, were dried to constant mass [139].

- ***Adsorption Isotherm*:** while the temperature is constant at 23 °C (±0.5), the test specimens were exposed to six sets of increasing humidity between 0% and 95%.
- ***Desorption Isotherm***: in the climate chamber and at 23 °C (±0.5), the process was reversed by exposing the test specimens to decreasing relative humidity from 95% to 0%.

Relative humidity conditions used for the test are shown in Table 3-9 below.

Table 3-9 Saturated Salt Solutions and Correspondent RH% Level for the Sorption Isotherm Test(ISO 12571:2013)

No.	Substance	RH (%) @23 °C
1	KOH	9
2	$MgCl2·6H2O$	33
3	$Mg (NO3)2·6H2O$	53

4	NaCl	75
5	KCl	85
6	KNO3	93

3.5.1.3.2 Equipment

- **Airtight box:** to be used as a climatic chamber.
- **Glass tray** to contain the saturated salt solution.
- **Analytical balance.**

3.5.1.3.3 Test Procedure

A) Sorption Curve

(See Fig 3-8 below) The specimens were dried to constant mass according to the British standard BS EN ISO 12570, 2018 [139]. Periodical weightings of the test specimen (every 24h) were performed until a constant mass was reached. At first, the specimens were placed inside the climate chamber with the lowest relative humidity (0%). The process was then repeated by increasing the relative humidity, as shown in Table.3-10 below.

B) Desorption Curve

The starting point of the desorption isotherm was at 95% relative humidity. Periodical weightings of the test specimen (every 24h) were performed until a constant mass was reached. The process was repeated by withering the relative humidity, as seen in Table 3-10 below.

Table 3-10 Relative Humidity Cycles for Sorption and Desorption Curves

Sorption	Relative humidity%	Desorption	Relative humidity%
Step 1	0	Step 1	95
Step 2	33	Step 2	85
Step 3	53	Step 3	75
Step 4	75	Step 4	53
Step 5	85	Step 5	33
Step 6	95	Step 6	0

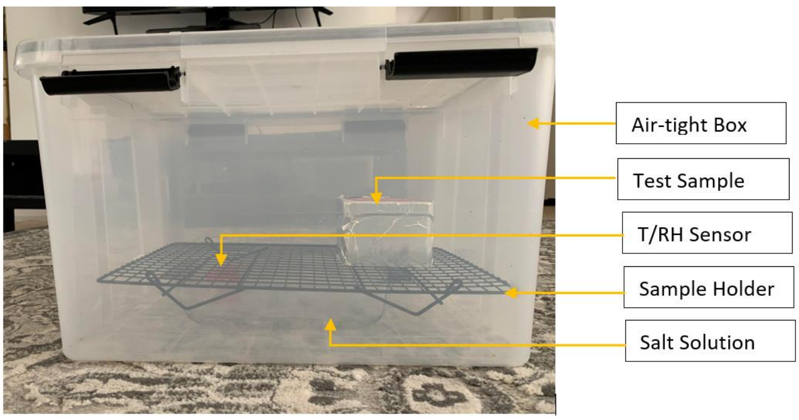


Figure 3-8 test Assembly For the Sorption Isotherm Test

3.5.1.3.4 Calculations

The moisture content mass by mass of the test specimens was calculated by:

$$U = (\frac{m-m_0}{m_0}) \qquad (3.6)$$

Where:

U= moisture content in an equilibrium state, m_0= mass of the specimen at dry condition (g), m= mass of the specimen at the equilibrium moisture content (g)

Equation 3.7 was used to calculate the moisture content by volume;

$$W = U\,P0 \qquad (3.7)$$

Where:

U is the moisture content mass by mass, and P0 is the density of dry material.

Equation 3.8 was applied to calculate the moisture content volume by volume:

$$\Psi = U\frac{P_0}{P_w} \qquad (3.8)$$

Where:

U is the moisture content mass by mass, P0 is the density of dry material, and Pw is the density of water (pw= 997.6 Kg/m^3 at 23 °C) [135] .

3.5.1.4 Water Absorption Coefficient (Aw), ((Kg/(m²√t))

The objective of the test is to determine the mass of water absorbed by the test specimen over time. The bottom face of a test specimen is immersed in water over a period, usually 24h. The water absorption coefficient is determined by measuring the change in the specimen's mass (see 2.2.3.9 for more details).

3.5.1.4.1 Methodology

The water absorption coefficient for the selected construction materials is determined following the British standard [87].

The bottom surface of the test specimen is in contact with water over a period, usually 24 hours. The water absorption coefficient is then determined by measuring the change in the mass of the test specimens. Before weighing the specimens, the water adhering to the surface and not absorbed by the specimen is completely removed.

3.5.1.4.2 Equipment

- **Analytical balance** with an accuracy of 0,1 g

- **Water tank** in which the water level should be kept constant at ±2mm. The tank should include point support to keep the specimen at least 5mm clear of the base.
- **Timer** accurate to at least 1 second in 24 hours.

3.5.1.4.3 Test Procedure

A minimum of three test specimens with a water contact area of 100 cm² or more were conditioned according to the British standard [87]. The sides of the specimens are sealed with water and vapour-tight sealant. The specimens are then placed in a tank resting on-point support so that the bottom surface of the specimens does not touch the surface of the tank (see Fig 3-9). The tank is then filled with water so that the water level is about 5 ± 2 mm above the highest point of the bottom face of the specimen.

Weighings of the specimens were performed from the beginning at the following time intervals: 5 minutes, 20 minutes, 1 hour, 2 hours, 4 hours, 8 hours, and two more times, including one at the 24th hour.

Figure 3-9 Test Assembly For the Water Absorption Coefficient (Aw) Test

3.5.1.4.4 Calculations

To calculate the difference of mass between each weighing and the initial weighing:

$$W = \frac{m_t - m_i}{\alpha} \qquad (3.10)$$

Where:

m_t= mass at each weighing (kg), m_i= mass at the initial weighing (kg), α= surface area of the specimen in contact with water (m²).

This is then plotted against the square root of weighing times, which will result in one of two graphs:

Type A, where the results of plotting Δm_t $agints$ $\sqrt{t}$ is a straight line, the water absorption coefficient can be calculated by:

$$A_w = \frac{\Delta m'_{tf} - \Delta m'_0}{\sqrt{t_f}} \qquad (3.11)$$

Where:

$\Delta m'_{tf}$= value of Δm on the straight line at time tf (kg/m²), t_f= duration of the test in seconds, which is usually one day.

Or

$$W_w = \frac{\Delta m\prime_{tf} - \Delta m\prime_0}{\sqrt{t_f}} \qquad (3.12)$$

Where t_f= duration of the test in hours, which is usually one day.

Type B, where the results of plotting Δm_t $aginst$ $\sqrt{t}$ is not a straight line but some kind of curve. In this case, the water absorption coefficient can be calculated by:

$$A_{w,24} = \frac{\Delta m\prime_{tf}}{\sqrt{86400}} \qquad (3.13)$$

$$A_{w,24} = \frac{\Delta m\prime_{tf}}{\sqrt{24}} \qquad (3.14)$$

3.5.1.5 Density (ρ), (kg/m³)

The objective of the Density tests is to determine the mass per unit volume of a material. Density is a basic material property defined as mass divided by volume. The basic principle of the Density test is to dry the test specimens to a constant mass and then divide the mass (kg) by the volume (m³) [140] [139] .

3.5.1.5.1 Test Procedure

- The specimens were oven-dried till constant mass was reached.
- The volume was determined from the linear dimensions of the test specimens.

3.5.1.6 Determination of Thermal Conductivity, Diffusivity, and Specific Heat Capacity

- **Thermal Conductivity (λ), (W/m. K)**

The objective of this test is to determine the thermal resistance of a test specimen. The thermal conductivity of the selected materials was measured according to the British standard BS EN 12939 [141] (see 2.2.3.1 for more details).

Thermal Conductivity is defined by equation 1.3 below:

$$\lambda(W/m/K) = \frac{Q}{Ft\ \frac{\Delta T}{h}} \qquad (3.15)$$

where: Q is the amount of conducted heat, F is the area through which heat is conducted, t is the time of heat conduction, ΔT is the temperature difference, and h is the specimen thickness.

- **Specific Heat Capacity (C_p), (KJ/kg. K)**

The objective of the specific heat capacity test is to determine the amount of heat energy required to raise the temperature of a material by a certain amount, typically by one degree Celsius or one Kelvin. Specific heat capacity refers to the amount of heat needed to increase the temperature of a unit mass of material by 1 Calvin at constant pressure and is given by the following equations [142].

$$C_p = m^{-1}Cp = m^{-1}(dQ/dT)p \qquad (3.16)$$

Where: m is the mass of the specimen, C_p is heat capacity, and dQ is the quantity of heat necessary to raise the temperature of the material by *dT.*

- **Thermal Diffusivity (α), (m^2/s)**

The objective of the Thermal Diffusivity test is to determine the ability of a material to conduct heat through its structure. Thermal diffusivity is a measure of how quickly heat can travel through a material, and is the ratio of thermal Conductivity to the specific heat capacity of a material. The flowing equation gives Thermal Diffusivity:

$$\alpha \nabla^2 T = \frac{\partial T}{\partial t} \qquad (3.17)$$

Where: α= thermal diffusivity (m^2/s), T= temperature (K), t= time (s), K= thermal conductivity (W/m. K), ρ= density (kg/m^3), and C_p= specific heat capacity (J/kg. K).

Chapter 2 (Literature review) and Chapter 4 (Determination of Thermal Properties) provided further detail about each test, test setup, and test results.

3.5.1.6.1 Methodology

The thermal properties of the selected construction material samples were measured using ISOMET 2114 thermal analyser. Six different materials with flat surfaces and an area of at least 100*100 mm and a minimum thickness of 30mm were measured. To provide the required thickness, three layers of Camel's hair were stoked in top of each other with a final thickness of 30mm for the Camel's hair samples.

To minimise measurement errors and avoid any external influences, the measurements were conducted in an airtight box and were repeated at least three times for each material (see Figure 3-8). The average values for Thermal Conductivity, Volumetric Heat Capacity, and Thermal Diffusivity were obtained using a surface probe. Specific Heat Capacity was later calculated by dividing the Volumetric Heat Capacity by the Density [143].

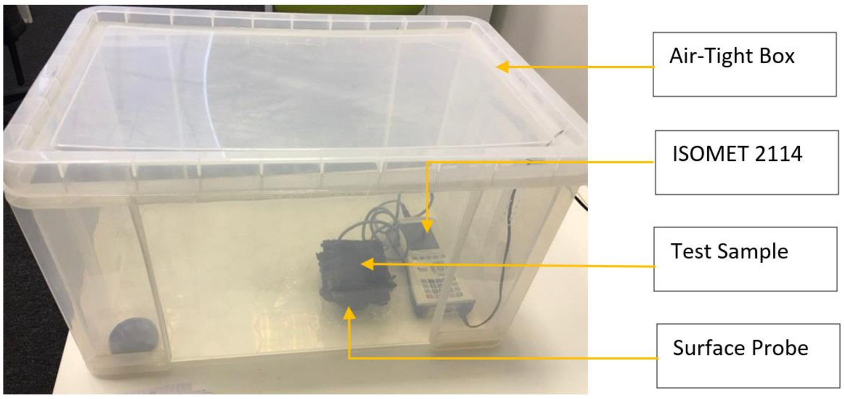


Figure 3-10 Experimental Setup for Measuring Thermal Properties

3.5.2 Description of Tools and Devices Use for the Experiments

The devices and tools used for testing the hygrothermal properties are described in this section.

- Airtight plastic boxes act as a climatic chamber. The boxes have the following dimensions: L59 x W39 x H29 cm (Figure 3-9).
- Wide glass dishes are to be used as containers for the salt solutions. The dishes' dimensions are 40 x 27 cm (Figure 3-10).
- Aluminium Foil Adhesive Duct Tape is used as specimen sealant (Figure 3-11).
- A cooling rack is to be used as a specimen holder. The rack has the following dimensions: 41 x25 cm. (Figure 3-12).
- Bluetooth thermometer sensor to measure the temperature and relative humidity inside the test chamber. In this study, Tempo Disc loggers were used. The specifications of the used sensor are shown in Table 3-11 below.
- Cooling fan to provide the required air velocity (for MBV Test). (Figure 3-13).
- Glass cube vases are to be used as either dry or wet test cups (for Water Vapour Diffusion Resistance Factor). The cups correspond to the shape and size of the test samples. Cube-shaped glass cups with 10 x 10 x10 cm dimensions were used (Figure 3-14.).
- Digital Calliper is capable of measuring to an accuracy of 0.2 mm (Figure 3-15.).
- Temperature Controller Thermostat to maintain the setpoint temperature inside the climate chamber (Figure 3-16.).
- Bonvoisin 0.01g Lab Scale (5000gx0.01g) was used during the experiments (Figure 3.17.).

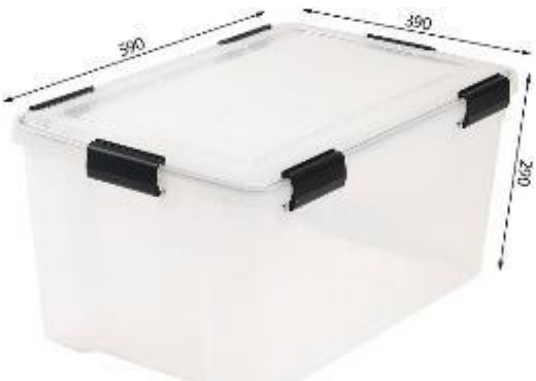


Figure 3-11 Airtight Plastic Box

Figure 3-12 Glass Dish

Figure 3-13 Aluminum Foil Adhesive Duct Tape

Figure 3-14 Cooling Rack

Table 3-11 Data logger Data loggers' specifications (Ref, Sensors manual)

Temperature range	-40°C to +85°C
Temperature Accuracy	0.4 °C
Relative pressure (hPa) full range	300 to 1110 hPa,
Barometric Pressure	+/-0.12hPA
Relative Humidity	0% - 100% RH
Accuracy of Relative Humidity	+/- 3%
Relative Humidity Resolution	0.1% RH

Figure 3-15 Cooling fan with the speed adjuster

Figure 3-16 Glass Cube Vase

Figure 3-17 Digital Calliper

Figure 3-18 Temperature Controller Thermostat

Figure 3-19 Analytical Balance

3.6 Numerical Simulations of Computer Models

Proposing a new wall construction for Libyan houses, using the data obtained from testing the hygrothermal properties of the construction material samples, is the main aim of this research. The thermal performance of the proposed wall and its possible impact on hygrothermal comfort will be assessed in Design-Builder and WUFI Plus. To ensure the accuracy of the simulations (see section 2.3), the building models of the Case Study Houses were calibrated in Design-Builder and WUFI Plus using the data obtained from monitoring the Case Studies.

3.6.1 Calibration of Building Models

The collected data from the monitoring was used to construct computer models for the three Case Studies. A simplified five-step calibration methodology (Figure 3-18) is adopted based on the review of published research (Chapter 2, section 2.3.4.). The proposed methodology consists of the following steps:

- **Step One**, Model Preparation.
- **Step Two**, Parameter Identification.
- **Step Three,** Sensitivity Analysis.
- **Step Four**, Adjustment of Parameters.
- **Step Five**, Results Analysis.

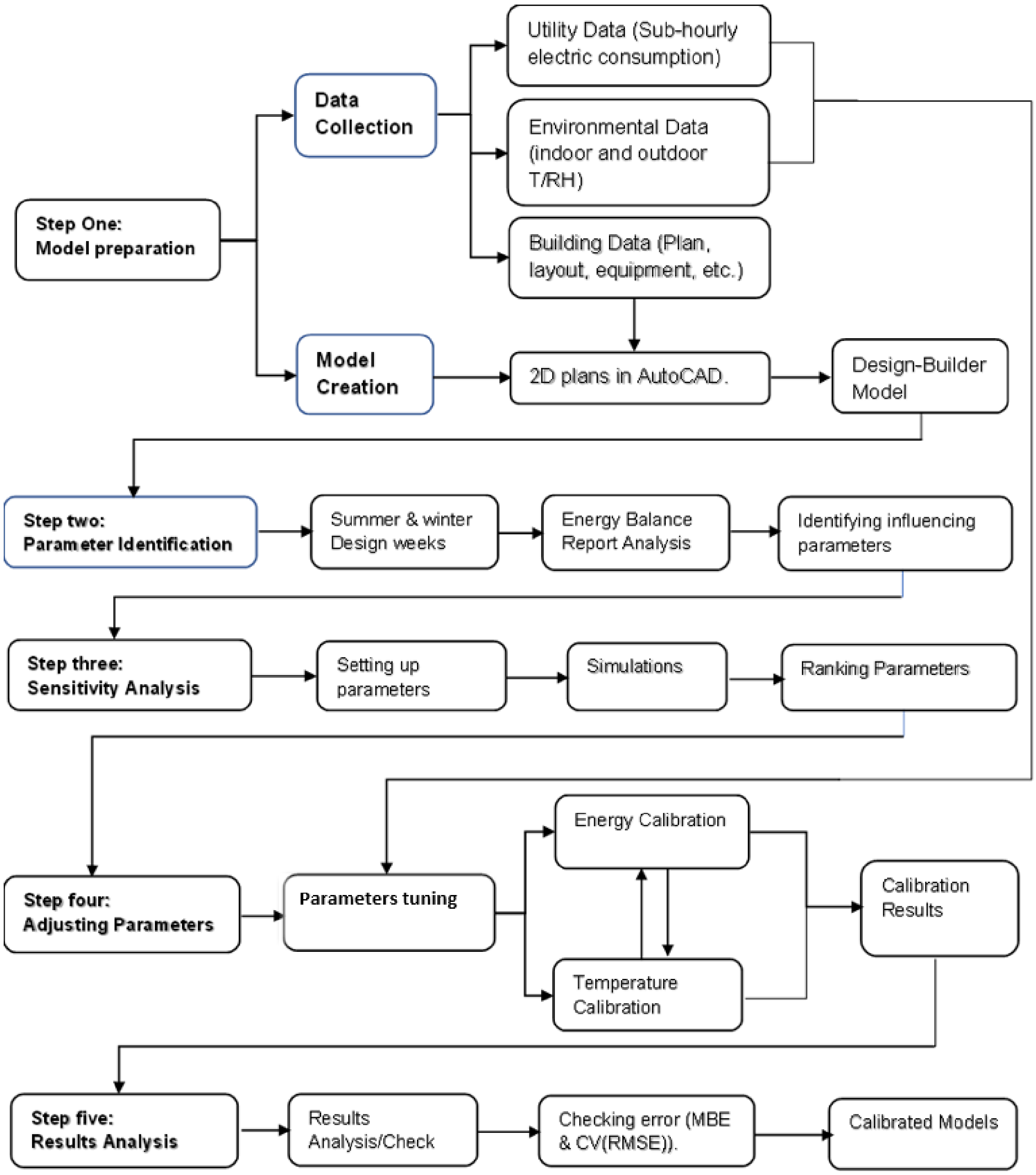


Figure 3-20 Proposed Calibration Methodology

3.6.1.1 Step One: Model Preparation

The first step is to prepare the computer models for simulation. This was done in the following two steps:

3.6.1.1.1 Data Collection

This step involves the collection of as much data as possible; for that, three sets of data were collected. The collected data include building data, environmental data, and utility data. Table 3-12 shows the types of data collected under each set.

Table 3-12 Data Collection Categories Use for Calibration

Building data	Environmental data	Utility data
1. Plan, orientation, and layout 2. Construction and envelope details 3. Occupancy 4. Equipment and operation 5. Lighting	1. Sub-hourly Indoor temperature and relative humidity 2. Sub-hourly outdoor temperature and relative humidity	1. Sub-hourly electric energy consumption 2. Plug load survey.

- **Building Data**

Building details data, such as design, shape and layout, room sizes, and dimensions, were gathered during the site visits to the Case Study houses. Electric loads lighting power density, and plug loads were surveyed at the building. Occupancy and operational schedules were determined by interviewing the occupants of the Case Study houses. In general, operation schedules were set at 100% from 07:00 to 23:00 during weekdays and at 20% during weekends and night-time (see Table 3-16).

- **Envelope Details;** The envelope input details for the three Case Study Houses were based on the author's personal experience and from interviewing the occupants of the Case Study houses. These can be found in section 5.1.

- **Environmental Data**

The environmental data includes indoor and outdoor temperature and relative humidity. These were collected on-site for each Case Study (see 3.3). The outdoor environmental data will be used to create the simulation weather files.

- **Indoor temperature and relative humidity:** Indoor environmental data was recorded at sub-hourly intervals. Detail of sensor and their location within the Case Studies can be found in section 3.3.2.4.
- **Outdoor temperature and relative humidity:** sub-hourly outdoor temperature and relative humidity data were obtained from outdoor data loggers outside of each of the Case Study Houses.

- **Utility Data**

Due to not having electricity meters in either of the Case Study Houses, "Tiny-Tag View 2 Current Logger TV-4810" was used to monitor the sub-hourly electricity consumption. The electricity consumption of the three Case Studies was calculated using equation (3.18) below.

$$Consumption = ((Current * Voltage)/1000)/0.5 \qquad \textbf{\textit{(3.18)}}$$

a) The first step was to multiply the current in milliamps (mA) by the voltage (V).

The declared voltage by the Libyan electricity company is 220-230 V. However, at the time of recording, the observed voltage was varying between 164V, 170V and 174V. therefore, the average of these three observed values was used for the calculation.

b) To convert the mA to kW, the values obtained from step (a) were multiplied by 1000.

c) As the recorded data was in a sub-hourly time interval, the values obtained from (b) in kW was divided by 0.5. This is to convert the kW to kWh.

From these calculations, the average Hourly, Daily and Monthly electricity consumptions were calculated

3.6.1.2 Building Models Creation

In this step, as the Case Study plans and drawings were unavailable, AutoCAD software was used to produce 2D drawings of the three Case Study Houses. The 2D drawings were exported to Design-Builder to create the 3D models. The 3D models created in Design-Builder were later exported to WUFI Plus.

3.6.1.3 Creating the Weather Files

When calibrating a model, one of the most important steps is to update and run the model using representative weather data corresponding to the same calendar days as the utility bill [144].

Design-Builder software provides hourly weather files for locations worldwide, including Libya, in WUFI However, the locations are more limited. Therefore, weather files for the 2020/2021 year were created from the external data loggers outside the Case Study Houses.

The data loggers recorded the Sub-hourly Temperature, Relative Humidity, and Dew-Point temperature (over 12 months period). Other data, such as global and diffuse horizontal solar radiation, wind speed and direction, Atmospheric pressure, direct normal radiation, and cloud cover, were obtained from the nearest weather station (approximately 34 km from the case study location and is located in the same region as the Case Study Houses).

The process of creating and editing the weather file was as follows:

- A template for a similar location in CSV format was created using the weather data translation tools.
- The CSV file, created in the first step, was loaded into a spreadsheet to be used as a template for the new weather file.
- The new data from the loggers were copied and pasted to the equivalent columns in the template spreadsheet created in the previous step.
- In all spreadsheet rows, the year was set to 2002, as required by Design-Builder.
- The CSV file was converted to EPW format using the Design-Builder’s weather file translator tool (a built-in tool used to convert weather files to different formats).

The weather files were checked for errors by running simulation sessions and checking the generated weather data from Design-Builder and WUFI Plus against the data obtained from the data loggers and the nearby weather station. The results of the study were highly satisfactory, demonstrating minimal error and a high degree of similarity between the simulated and measured weather data.

Fig 3-21 and 3-22 below show the average outdoor monthly temperature and relative humidity obtained from the outdoor data loggers outside the Case Study Houses.

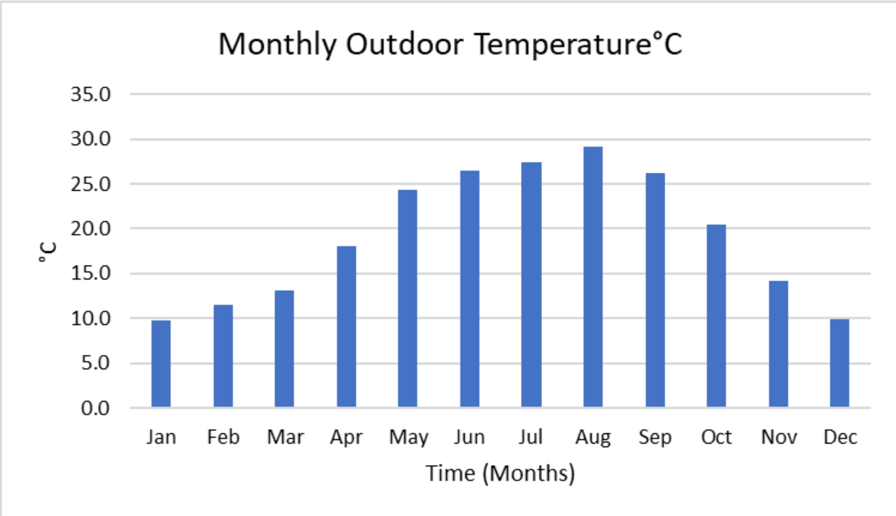


Figure 3-21 Average Monthly Outdoor Temperature (˚C) Of the Case Study Houses

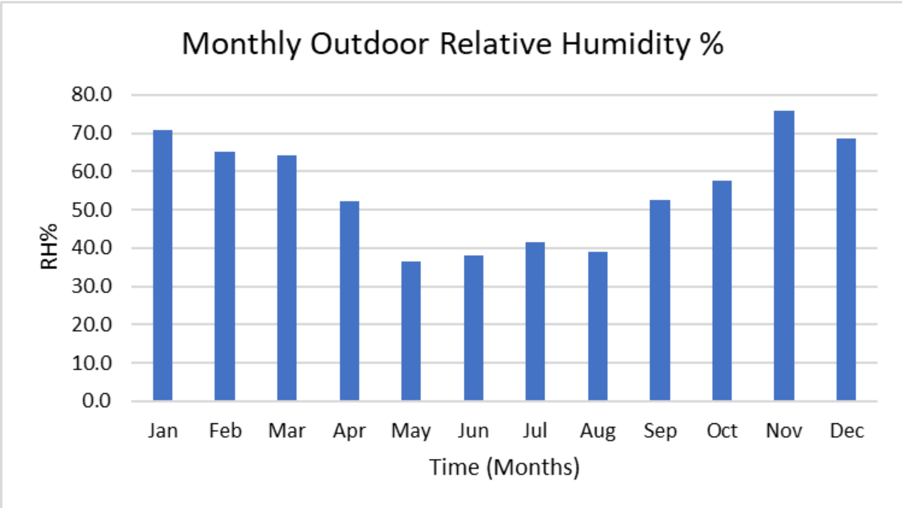


Figure 3-22 Average Monthly Outdoor Relative Humidity (%) Of the Case Study Houses

3.6.1.4 Defining Occupancy and Operation

The default occupancy and operation hours obtained from the Design-Builder and WUFI Plus libraries were used at the first calibration stage. A more detailed and as close to reality as possible occupancy and operations schedule were needed at later stages.

From Interviewing the occupants and analysing the indoor environmental and electricity consumption data, the initial weekdays and weekends occupancy and operation schedules were established for the three Case Studies, as seen in Table 3-13 below.

Table 3-13 Example of Occupancy and Operation Profile (Jan-Jul)

Weekend			Weekday		
Date	**Time**	**Intensity**	**Date**	**Time**	**Intensity**
25 January 2020	00:00-02:00	100%	27 January 2020	00:00-04:30	30%
	02:30-09:00	20%		05:00-08:00	90%
	09:30-15:00	60%		08:00-10:00	100%
	15:30-17:00	100%		10:30-12:00	50%
	17:30-23:30	60%		12:30-16:00	30%
				16:30-23:30	100%
07 February 2020	00:00-02:00	100%	02 February 2020	00:00-08:00	50%
	02:30-07:00	70%		08:30-12:00	100%
	07:30-10:00	20%		12:30-23:30	70%
	10:30-16:30	100%			
	17:00-20:00	30%			
	20:30-23:30	100%			
06 March 2020	00:00-09:30	30%	11 March 2020	00:00-02:30	60%
	90:30-15:00	100%		03:00-08:00	20%
	15:30-21:00	60%		08:30-11:00	60%
	21:30-23:30	30%		11:30-13:30	100%
				14:00-18:30	50%
				19:00-23:30	100%
11 April 2020	00:00-02:00	50%	13 April 2020	00:00-15:30	30%
	02:30-03:30	20%		16:00-18:00	70%
	04:00-05:00	70%		18:30-21:00	100%
	05:30-07:00	80%		21:30-23:30	70%
	07:30-08:30	30%			
	09:00-11:00	100%			
	11:30-16:00	50%			
	16:30-18:00	20%			
	18:30-21:00	60%			
	21:30-23:30	100%			
02 May 2020	00:00-02:00	20%	05 May 2020	00:00-17:00	30%
	02:30-04:00	90%		17:30-23:30	100%
	04:30-11:00	30%			
	11:30-05:30	90%			
	16:00-17:00	100%			
	17:30-19:00	80%			
	19:30-21:00	50%			
	21:30-23:30	90%			
	04:30-11:00	30%			
05 June 2020	00:00-10:00	50%	01 June 2020	00:00-12:00	50%
	10:30-19:00	60%		12:30-16:00	100%
	19:30-23:30	100%		16:30-23:30	70%
03 July 2020	00:00-04:00	100%	13 July 2020	00:00-03:00	100%
	40:30-80:30	50%		03:30-10:30	50%
	09:00-15:00	30%		11:00-16:00	80%
	15:30-19:00	50%		16:30-23:30	40%
	19:30-20:30	30%			
	21:00-23:00	50%			

In Table 3-13 above, the recorded sub-hourly energy consumption and the sub-hourly indoor temperature were used to generate operation and occupancy profiles, which will be used to create the operation and occupancy for the Base Case Models in both Design-Builder and WUFI Plus.
An example of the initial occupancy and operation profile inserted in Design-Builder and WUFI Plus can be found in the Appendices.

3.6.1.5 Step Two: Parameter Identification

According to Macdonald (2002) ,[145], the basic parameters for a building simulation procedure in a cold climate are thermophysical properties of construction materials, internal gain, and infiltration rates.
Westphal and Lamberts (2005), [118], proposed a practical method to identify heat sources in the buildings based on analysing the simulation reports of summer and winter design weeks by defining the highest heat gain or loss building component. This study will use the proposed method by Westphal and Lamberts (2005), [118].
After the models were created in the previous step, the next step is to run two initial simulation sessions, one for summer design week and one for the winter design week and analyse the energy balance reports of the Case Study models to identify the influencing heat gain and loss sources in the buildings. The most influencing heat gain and loss parameters of the three Case Studies are presented in Table 3-14 below. The most influencing heat gain or loss parameters specified in this step will receive more attention during the sensitivity analysis (Step three).

Table 3-14 Heat Gain and Loss parameters Of the Three Case Study Houses

Case Study House 1				
Component	**Heat Gains**			
	Summer		**Winter**	
	[W/²m]	**%**	**[W/²m]**	**%**
HVAC	2.1	35	6.3	43
Envelope	1.7	28	6.1	41
Equipment	0.8	14	1.1	8
Window	0.8	14	0.5	4
Infiltration	0.5	9	0.7	4
Case Study House 2				
Component	**Heat Gains**			
	Summer		**Winter**	
	[W/²m]	**%**	**[W/²m]**	**%**
HVAC	7.1	32.3	14	42
Envelope	5.9	26.8	5.9	17.7
Window	1.3	5.9	3.5	10.5
Infiltration	6.9	31.4	1.4	4.2
Lighting	0.5	2.3	0.5	1.5
Equipment	0.3	1.36	0.3	0.9
People	0.1	0.45	0.4	0.12
Case Study House 3				

Component	Heat Gains			
	Summer		Winter	
	[W/²m]	%	[W/²m]	%
Envelope	2.9	48	1.5	32
Window	1.8	30	1.7	37
Infiltration	0.7	12	0.9	18
Lighting	0.27	5	0.27	6
Equipment	0.25	4	0.25	6
People	0.03	0.46	0.07	2

3.6.1.6 Step Three: Sensitivity Analysis

Sensitivity analysis is a qualitative comparison between the change in the output and the change in the input [146]. Moreover, if parameter A causes a change to parameter B and the change in both can be measured, then the sensitivity of A can be determined with respect to B. Therefore, sensitivity analysis is an analysis of the input and output of the simulation system [146].

The previous step identified a few building components as the highest influencing heat gain and loss parameters for each case study building. After defining the critical building parameters (see Table 3-14), in step two, the next step is to perform a sensitivity analysis by varying the input values for each building component under investigation and measuring the change in the output. The sensitivity analysis will be performed by changing the input values of those parameters, starting with the parameters that ranked highest. The variables related to each parameter, which will undergo the sensitivity analysis, are listed in Table 3-15 below.

Table 3-15 Building Heat Sources and Input Variables

Heat source	Input variable
HVAC	- Coefficient of performance (CoP) - Schedule and operation - Setpoint and setback
Envelope	**Walls** - Dimensions (total area and azimuth) - U-value - Construction materials - Material's thermal Conductivity
Windows	- Dimensions (WWR and Floor-to floor height) - U-value - Shading coefficient - Solar protection - Glazing type - Glazing thickness
Equipment	**Equipment (TV, boiler, etc.).** - Power - Schedule **Lights** - Power - Schedule
Infiltration	- Infiltration rate with schedules

The influence coefficient (IC%) is calculated from the equation below [118] [146].

$$IC = \frac{\Delta OP \div OP_{BC}}{\Delta IP \div IP_{BC}} X100 \qquad (3.19)$$

Where:

- ***IC=*** influence coefficient
- ***ΔOP*** and ***ΔIP*** = change in output and input, respectively.
- ***OPBC*** *and* ***IPBC*** = the output and the input base case values, respectively.

Once the IC calculations are done for each parameter, the input variables will be sorted from the highest influence coefficient to the lowest. The input parameters ranked first will be the target for any further adjustment if needed (step four of the calibration).

3.6.1.7 Step Four: Adjusting Input Parameters

In the previous step, building parameters and their influence on the heating and cooling loads and indoor temperature were defined and ranked in terms of IC% from highest to lowest. In this step, a systematic adjustment, and manual tuning of the building parameters, with more focus on the parameters that ranked highest through the sensitivity analysis, will be performed.

In this step, three main simulation sessions will be performed, with a series of simulation runs for each session. The main simulation sessions are as follows:

- A session for energy consumption calibration.
- A session for zone temperature calibration.
- A session for final tuning of the calibration.

3.6.1.7.1 Energy Consumption Calibration

In this step, several simulation sessions were performed to calibrate the monthly electricity consumption for each of the three Case Study Houses. The parameters that will be tuned are shown in Table 3-14 above (Energy Parameters). After a few simulation runs and varying some of the energy parameters (shown in Table 3-14), the monthly energy consumption was calibrated. The indoor zoon temperature will be calibrated in the next simulation session.

3.6.1.7.2 Zone Temperature Calibration

In the first simulation session, the energy consumption of the three Case Study Houses was calibrated. However, there was an unacceptable performance gap in the indoor temperature. Therefore, a manual adjustment of the temperature parameters (Parameters that ranked highest in the sensitivity analysis) were performed for each case study house.

3.6.1.7.3 Finalising The Calibration

After calibrating the energy and the zone temperature for the three Case Study Houses, a final simulation session and adjustment of the monthly measured and simulated energy and zone temperature were done. The results of calibrating the energy consumption, indoor temperature, and indoor relative humidity in Design-Builder and WUFI Plus are presented in subsection 5.1.2.

3.6.1.8 Step Five: Results Analysis

Mean Bias Error (MBE) and Cumulative Variation of Root Mean Squared Error (CV(RMSE)) values were calculated using the following formulas:

- **Mean Bias Error (MBE)**

$$MBE = \frac{\sum_{i}^{Np}(M_i - S_i)}{\sum_{i=1}^{N_P} M_i} \quad \textbf{\textit{(3.21)}}$$

- **Cumulative Variation of Root Mean Squared Error (CVRMSE)**

$$CV(RMSE)_P = \frac{\sqrt{\sum_{i=1}^{N_P}(M_i - S_i)^2 / Np}}{\bar{M}\rho} \quad \textbf{\textit{(3.22)}}$$

$$\bar{M}_P = \frac{\sum_{i=1}^{N_P} M_i}{N_P} \quad \textbf{\textit{(3.23)}}$$

Where: $\boldsymbol{M}_i$ and $\boldsymbol{S_i}$ are measured and simulated data at instance *i,* respectively, P is the time interval (i.e., monthly, weekly, daily, and hourly), Np is the number of values at interval p (i.e., N month =12, N Day= 360, N hour= 8760), Mp is the average of the measured data.

3.6.1.8.1 Acceptable Limits

ASHRAE guideline 14 gives the acceptable limits for calibration to hourly data as -10% ≤ MBE hourly ≥10% and CV(RMSE) hourly ≤30%, monthly data as -5% ≤ MBE monthly ≤5%, and CV(RMSE) monthly ≤15%.

3.6.1.9 Observations From the Calibration In Design-Builder and WUFI Plus

This chapter used Design-Builder and WUFI Plus to calibrate the Case Study models. This subsection reports on observations from the calibration in both software.

❖ **Location and Weather files**

WUFI Plus Climate database is limited to Europe, Japan, Oceania, South America, South Asia, the USA, and North America. On the other hand, Design-Builder offers more locations covering almost all parts of the world. Both software, however, accepts external weather files in various formats and are reasonably straightforward to use.

❖ **Layout and Design**

In terms of design and layout, Design-Builder is far easier and more flexible to use, while WUFI Plus is limited to three plan shapes. However, it is possible to import external drawing files to WUFI Plus (using gbXML to WUFI Plus XML-Project file converter tool) and Design-Builder to simulate more complex geometries. 3D models from Design-Builder can also be exported to WUFI Plus using the gbXML to WUFI Plus XML-Project file converter. Though, alternations on the model's input, such as envelope, weather, and material data, might be required before running simulations.

❖ **Envelope and Material**

Both software offers a vast building material library for simulations. It is allowed in both software to edit and add new material. In Design-Builder, Specific Heat Capacity, Thermal Conductivity, and Density are required at a minimum, and simulation can be run if these three values are available. In WUFI Plus, however, more material properties (in addition to the ones required in Design-Builder), such as Porosity and Water Vapour Diffusion Resistance Factor, are the minimum necessary material data before running any simulations.

3.7 Numerical Simulations of Computer Models in Design-Builder and WUFI Plus

Keeping a constant thickness (between 250-350mm as is used in the contemporary Libyan houses), different wall configurations for each building material (Table 3-16 and Figure 3-23) will be simulated in Design-Builder and WUFI Plus to assess any potential impact changing the wall's materials might have on the indoor hygrothermal conditions.

A sensitivity analysis (to test the impact of changing the wall materials and the impact of wall design on the hygrothermal condition of the Test Cell Model), was performed to reduce the number of simulation runs.

The first step of the sensitivity analysis was performed to define which of the building materials (Limestone, Hollow Concrete, Mud block, Sandstone, Camel's hair and Clay) has the highest impact on indoor hygrothermal conditions. The second step of the sensitivity analysis was performed to identify which of the wall configuration (using the identified materials from the first step- see Table 3-16) would have the highest impact on the hygrothermal conditions of the Benchmark model. The sensitivity analysis helped reduce the required simulation runs from 190 runs to only 8 runs in both Design-Builder and WUFI Plus.

The methodology for building performance simulations in Design-Builder and WUFI Plus is explained in more detail in the following subsections.

3.7.1 Simulation Tools

The simulations will be performed using two simulation tools, Design-Builder and WUFI Plus.

- ***Design-Builder*** is a "Qualified Computer Software" used to calculate energy efficiency and indoor environment. The software has been tested under the comparative Standard Method of Test for the evaluation of Building Energy Analysis Computer Programs BESTEST/ASHARE STD 140 (Building Energy Simulation Test) [147].

- ***WUFI Plus*** is a simulation tool that, in addition to simulating the hygrothermal condition in building components, the software also simulates the temperature and relative humidity of the indoor environment and is suitable for simulating energy consumption as well. WUFI Plus was validated and corresponded to BS EN 15026 [148] [149].

3.7.2 Weather Data

Actual weather data was recorded using an on-site weather station and is used for the simulation in both software (see 3.6.1.3.).

3.7.3 Material Data

The standard wall types of the modern houses of Libya comprise either Limestone or Hollow Concrete with Cement plaster and Cement mortar. The thickness of the wall is about 250-350 mm. the envelope is uninsulated, and roofs are usually made of reinforced concrete (150 -200 mm) or Hollow Concrete with Cast concrete (250-300 mm) [6]. Conventionally, some other wall materials, such as Sandstone, Mud Blocks, Clay, Camel Hair tents, and Limestone, were used. Table 3-15 below are the material dimensions as provided by manufacturers and as found in practice.

Table 3-16 Material Details

Material	Thickness mm	Use
Limestone	200-300	Wall material
Hollow concrete	200-300	Wall material
Mud Block	200-300	Wall material
Sandstone	200-300	Wall material
Cement	25	Plaster
Clay	25	Plaster
Camels' hair	100	Insulation

The above-listed materials were tested for the following hygrothermal properties (see Chapter.4): Moisture Buffer Value (MBV), Water Vapor Diffusion Resistance Factor (µ Value), Sorption Isotherm (u), Water Absorption Coefficient (Aw), Density (ρ), Thermal Conductivity (λ), Thermal Diffusivity (α), and Specific Heat Capacity (C_p). The porosity data was obtained from WUFI Plus Data-Base and relevant published research. The results from chapter 4 are used as a database for the simulation in Design-Builder and WUFI Plus in chapter 5.

3.7.4 Simulation Runs and Wall Configurations

Six different building materials from Libya were tested for their hygrothermal properties, and the results are presented in chapter 4 of this thesis. Using the selected materials, Limestone (LS), Hollow Concrete (HC), Sandstone (SS), Mud Block (MB), Camel’s hair (CH), and Clay (CL), ten different wall configurations (W1-W8) will be tested in Design-Builder and WUFI Plus.

Figure 3-19 below is the wall configurations, and Table 3-16 below is the material combination details for each proposed wall.

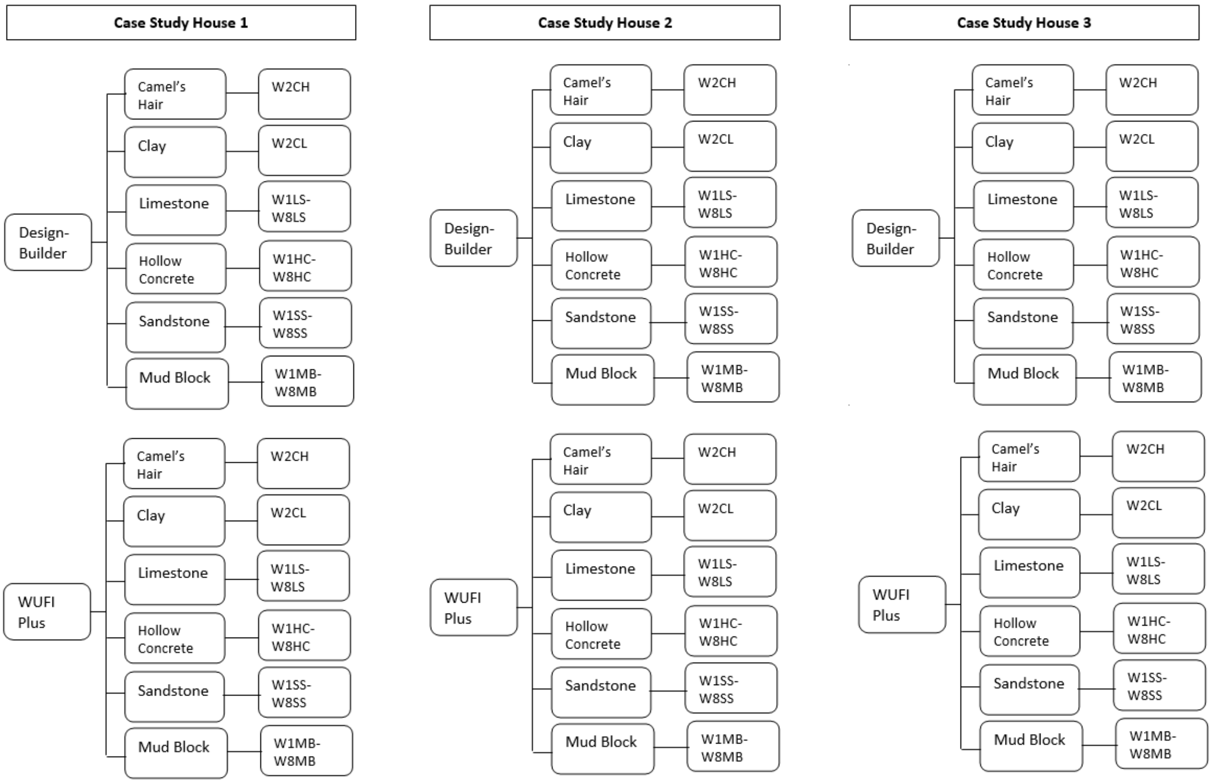


Figure 3-23 Proposed Wall Configurations (W1-W8) Using the Selected Materials

Table 3-17 Wall Configurations and their Corresponding Acronyms and U-value

Acronyms	Wall Configuration	U-Value (W ²m/K)	Acronyms	Wall Configuration	U-Value (W ²m/K)
W2CH	Camel Hair+ Clay Plaster 350 mm	0.285	W2CL	Clay 300	1.636
Acronyms	**Wall Configuration**	**U-Value (W ²m/K)**	**Acronyms**	**Wall Configuration**	**U-Value (W ²m/K)**
W1LS	Limestone 200 mm	1.627	W1HC	Hollow Concrete 200 mm	2.613
W2LS	Limestone 300 mm	1.195	W2HC	Hollow Concrete 300 mm	2.044
W3LS	Limestone +Cement Plaster (250mm)	1.462	W3HC	Hollow Concrete +Cement Plaster (250mm)	2.211
W4LS	Limestone +Cement Plaster (350mm)	1.104	W4HC	Hollow Concrete +Cement Plaster (350mm)	1.79
W5LS	Limestone +Clay Plaster (250mm)	1.454	W5HC	Hollow Concrete +Clay Plaster (250mm)	2.201
W6LS	Limestone +Clay Plaster (350mm)	1.099	W6HC	Hollow Concrete +Clay Plaster (350mm)	1.7
W7LS	Limestone +Camel hair insulation +Cement Plaster (350mm)	0.557	W7HC	Hollow Concrete +Camel hair insulation +Cement Plaster (350mm)	0.638
W8LS	Limestone +Camel hair insulation +Clay Plaster (350mm)	0.556	W8HC	Hollow Concrete +Camel hair insulation +Clay Plaster (350mm)	0.638
Acronyms	**Wall Configuration**	**U-Value (W ²m/K)**	**Acronyms**	**Wall Configuration**	**U-Value (W ²m/K)**
W1MB	Mud Block 200 mm	2.233	W1SS	Sandstone 200 mm	2.613
W2MB	Mud Block 300 mm	1.75	W2SS	Sandstone 300 mm	2.044
W3MB	Mud Block +Cement Plaster (250mm)	1.933	W3SS	Sandstone +Cement Plaster (250mm)	2.211
W4MB	Mud Block +Cement Plaster (350mm)	1.524	W4SS	Sandstone +Cement Plaster (350mm)	1.79
W5MB	Mud Block +Clay Plaster (250mm)	1.923	W5SS	Sandstone +Clay Plaster (250mm)	2.201

W6MB	Mud Block +Clay Plaster (350mm)	1.514	W6SS	Sandstone +Clay Plaster (350mm)	1.7
W7MB	Mud Block +Camel hair insulation +Cement Plaster (350mm)	0.613	W7SS	Sandstone +Camel hair insulation +Cement Plaster (350mm)	0.638
W8MB	Mud Block +Camel hair insulation +Clay Plaster (350mm)	0.612	W8SS	Sandstone +Camel hair insulation +Clay Plaster (350mm)	0.638

The table showed that wall W2CH (Camel's hair+ Clay Plaster 350mm) had the lowest U-value compared to the other walls. The table also showed that adding a layer of Camel's hair insulation can help improve the U-value of a wall significantly compared to a wall with the same thickness but with no insulations. It was also noted that adding a plaster layer (either Clay or Cement) does not affect the wall's thermal insulation properties.

The figures below show examples of each of the wall types.

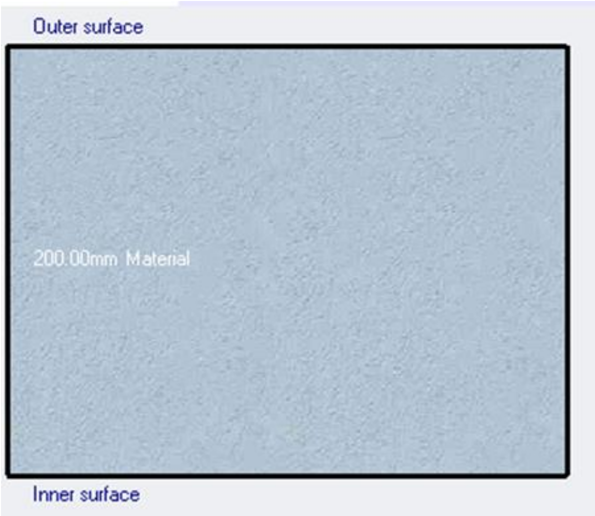


Figure 3-24 Example of Wall W1

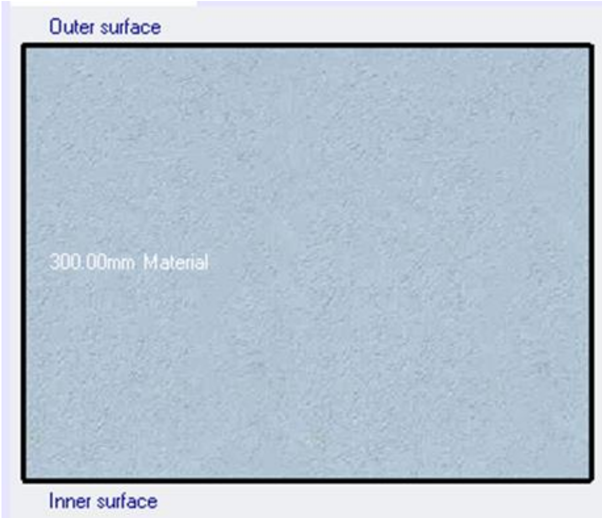


Figure 3-25 Example of Wall W2

(Material Limestone, Hollow Concrete, Mud Block, Sandstone, Camel's hair or Clay(200mm or 300mm)

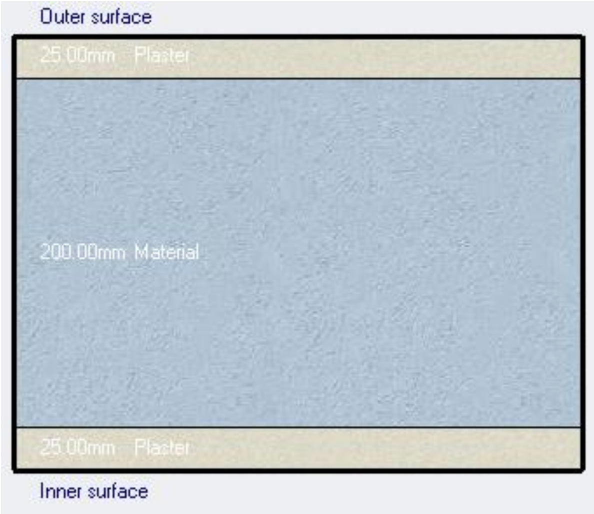


Figure 3-26 Example of Walls W3 and W5 **Figure 3-27 Example of Walls W4 and W6**

(Plaster= Clay or Cement (25mm), Material Limestone, Hollow Concrete, Mud Block or Sandstone (200mm or 300mm)).

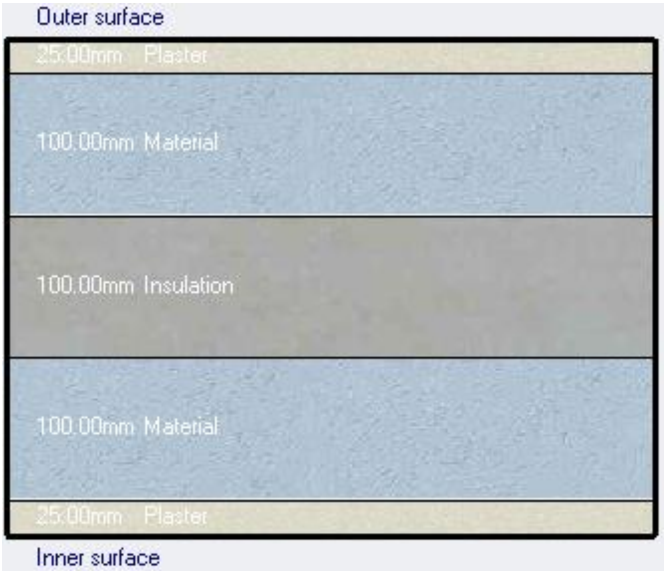


Figure 3-28 Example of Walls W7 and W8

(Plaster= Clay or Cement(25mm)-Material Limestone, Hollow Concrete, Mud Block or Sandstone(100mm)-insulation= Camel's Hair(100mm)).

3.7.5 Sensitivity Analysis

The objective of the sensitivity analysis is to try to reduce the number of simulations by focusing only on wall configurations with the highest impact on indoor Relative Humidity, Air Temperature, Radiant Temperature, and Operative Temperature. Wall configurations with the highest impact on these parameters will be approved for simulation to evaluate further their impact on the hygrothermal comfort of the Case Study Houses.

The first step in the sensitivity analysis is to identify which tested materials have the highest impact on the hygrothermal conditions of the Test Cell Model. After identifying the building material with the highest impact, the second step is to test which wall configurations would have the highest impact on the hygrothermal conditions of the Test Cell Model.

Case study House-3 (free-running house) was chosen as a Test Cell Model to perform the sensitivity analysis as the house uses no heating or cooling devices; therefore, the influence of mechanical heating and cooling equipment is neglected.

Heat balance reports of the Case Study Houses (See 5.2.2.) showed high solar gains through the roof and windows. This solar gain must be minimised to understand the selected walls' hygrothermal performance fully. In their study, Gabril, 2014 [6] suggested that roofs with a U-value of 0.402 (W/ m^2K) are suitable for the Libyan climate and can provide adequate insulation for Libyan houses. Hence, the recommended value by Gabril, 2014 was used for the Test Cell Model's roof. Windows and floors were also optimized for the Test Cell Model. The Windows were assumed to be double-glazed with a U value of 2.8 (W/ m^2K), and the floor's U-value was assumed to be 0.65 (W/ m^2K) according to the suggestions from Gabril, 2014 [6].

The first set of the simulation was performed using the following materials Limestone (LS), Mud Block (MB), Clay (CL), Hollow Concrete (HC), Sandstone (SS), and Camel's Hair (CH). This step identified which of the building material had the highest impact on the hygrothermal conditions of the Test Cell Model.

After identifying which of the building materials had the highest impact on the hygrothermal conditions of the Test Cell model, wall configurations (W1-W8, see Table 3-28 and Figures 3-24 to 3-28) using the highest ranked material (identified from the first step) were simulated in Design-builder and WUFI Plus. This step identified which wall configuration had the highest impact on the hygrothermal conditions of the Test Cell Model.

This section's outcome helped reduce the required simulations by focusing only on materials and wall configurations with the highest impact on the Test Cell Model's indoor temperature and relative humidity.

3.7.6 Hygrothermal Behaviour Modelling

This section studies the long-term hygrothermal behaviour of the selected walls from the sensitivity analysis.

The hygrothermal simulations in WUFI 2D were carried out for high indoor moisture load, which was estimated by the software following the European standard for "assessing moisture transfer through building components and building elements by numerical simulation" EN 15026 (2007) [150]. In EN 15026 (2007), the indoor climate can be determined from an external file. The external conditions were generated using a real weather file, the same weather file used for the computer model calibration (section 3.6.1.3.) and will also be used for the hygrothermal simulation of the Case Study Houses in Design-Builder and WUFI Plus.

The orientation of the walls is north, where the solar radiation is low, and the driving rain is relatively high. It should be mentioned that the average annual rain fall is between 50mm and 400mm between the months of September and March[151] .

When a material is wet, it has a higher thermal conductivity and a lower thermal resistance compared to when it is dry. This means that heat can be transferred more easily through the wet material. Therefore, when simulating the heat and moisture transfer in a building component, it is essential to start from a wet condition to accurately capture the impact of moisture on the thermal behaviour of the material. Starting from a dry condition would not give an accurate representation of the heat and moisture transfer as it does not consider the impact of moisture on the material's thermal properties. Moreover, starting from a wet condition helps to identify potential moisture problems and prevent damage to building components, as it allows for the assessment of the drying potential of a building material. Therefore, The initial relative humidity in the walls was assumed to be 80%, and the temperature at 20 ^{o}C. The simulation period is four years to assess the drying impact of the wall over time.

3.7.6.1 Hygrothermal Evaluation Criteria

The objective of the simulation is to evaluate the hygrothermal behaviour of the selected walls from the sensitivity analysis and to detect any potential risks of condensation, dryness and mould growth within these walls. The criteria used to assess the hygrothermal behaviour of the selected walls have been used by several researchers [152], [153] and are the Following;

- **Total Moisture Content (TMC);** to indicates the wall's capability to dry with time. The selected walls' initial and final moisture content are evaluated over four years. The final moisture content must be lower than the initial moisture content for the wall to pass this criterion.
- **Dryness rate (DR);** the dryness rate is calculated for the selected walls over four years. The dryness rate is an expression of the difference between the final and initial moisture content as a percentage. The higher the dryness rate, the faster the wall dries over time. The DR can be calculated using the equation below.

$$\mathrm{DR} = \frac{\mathrm{TWC_i} - \mathrm{TWC_f}}{\mathrm{TWC_i}} \times 100 \qquad (3.24)$$

Where: TWC_i is the initial moisture content, and TWC_f is the final moisture content.

- **Condensation Risk:** condensation is likely to occur if the surface temperature of the wall is lower than the dew point temperature of the indoor air. Condensation risk is evaluated by comparing the surface temperature to the indoor dew point air temperature for the selected walls; the longer the surface temperature is lower than the dew point temperature, the greater the risk.
- **Mould growth:** mould can grow when the hygrothermal conditions reach a certain threshold, known as the LIM (lowest isopleth for mould). The LIM is governed by the materials temperature, relative humidity, exposure period and the material's properties. There are two isopleth limits. LIMB1 for biodegradable materials, such as wallpapers and plasters board, and LIMB2 for non-biodegradable materials [154], [155], such as plasters and mineral building materials. If the conditions are above the isopleth limits, mould growth is likely.
- **ASHRAE creation:** ASHRAE Standard 160- specifies the following conditions to be met: A 30-day running average surface relative humidity should be less than 80% when the 30-day running average surface temperature is between 5 ◦ C and 41 ◦ C. Surface temperatures and RH were averaged over 30 days and compared to the ASHRAE 160-2009 limits.

3.7.7 Thermal Comfort Assessment in Design-Builder and WUFI Plus

The impact of changing the wall assembly on the thermal comfort of the Case Study Houses will be assessed using Fanger's Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfaction (PPD) thermal comfort indicators. The two indicators (PMV and PPD) are widely used in surveys of indoor thermal comfort [156]. And are used to predict the percentage of dissatisfied occupants from indoor thermal conditions according to ISO 7732 [157]. The PMV and PDD can be respectively calculated from the equations below:

$$PMV = (0.03e^{-0.036M} + 0.028) \times \{(M - W) - 3.05 \times 10^{-3} \times [5733 - 6.99(M - W) - P_a] - 0.42 \times [(M - W) - 58.15] - 1.7 \times 10^{-5} M(5867 - P_a) - 0.0014M(34 - T_a) - 3.96 \times 10^{-8} \times f_{cl} \times [(T_{cl} + 273)^4 - (T_r + 273)^4] - f_{cl} h_c (T_{cl} - T_a)\} \tag{3.24}$$

$$T_{cl} = 36.7 - 0.028(M - W) - I_{cl}\{3.96 \times 10^{-8} f_{cl} \times (T_{cl+273})^4 - (T_r + 273)^4] + f_{cl} h_c (T_{cl} - T_a)\} \tag{3.25}$$

$$h_c = \begin{cases} 2.38(T_{cl} - T_a)^{0.25} & when\ 2.38|T_{cl} - T_a|^{0.25} > 12.1\sqrt{v_{ar}} \\ 12.1\sqrt{v_{ar}} & when\ 2.38|T_{cl} - T_a|^{0.25} < 12.1\sqrt{v_{ar}} \end{cases} \tag{3.26}$$

$$f_{cl} = \begin{cases} 1.000 + 1.290 \times I_{cl} & when\ I_{cl} \le 0.078m^2\, K/m \\ 12.1\sqrt{v_{ar}} & when\ I_{cl} > 0.078m^2\, K/m \end{cases} \tag{3.27}$$

Where:

M= Metabolic rate (W/m²)
W=Effective mechanical power (W/m²)
$I_{cl}$is = Clothing insulation, (m² · K/W)
f_{cl}=Clothing surface area factor
T_a= Air temperature (̊C)

T_r= Mean radiant temperature (˚C)
v_{ar}= Relative air velocity (m/s)
pa = Water vapour partial pressure (Pa)
h_c= Convective heat transfer coefficient [W/(m².K)]
t_{cl}=Clothing surface temperature (˚C).

With the PMV determined, the PPD can be calculated with the equation below:

$$PPD = 100 - 95.\exp\left(-0.033\,53.PMV^4 - 0.217.PMV^2\right) \qquad (3.28)$$

The required parameters for the thermal comfort assessment include Air temperature, radiant temperature, relative humidity, and air velocity. The temperature and relative humidity were obtained from monitoring the Case Study Houses, and air velocity was estimated at 0.1 m/s. The metabolic rate of 0.7 met ((70 W/person (sleeping)) and 1.0 met (100 W/person (Seated, quiet/Reading, Seated) were used for the Bedrooms and Living rooms of the Case Study Houses, respectively. Clo-value of 1 (Typical winter clothing) was used for cold months (November-March), and 0.74 clo (Sweat pants, long-sleeve sweatshirt) was used for moderate months (April and October). Typical summer clothing (0.5 clo) was used for the hot months (May-September) [158].

3.7.8 Energy Saving Potentials

This subsection will present a comparative study of the selected four wall assemblies and their impact on operational energy. For this reason, the calibrated models of Case Study House-1 and Case Study House-2 were used for the simulations in Design-Builder and WUFI Plus. The parameter that will be used to assess the energy-saving potentials are:

- Total cooling (kWh)
- Sensible cooling (kWh)
- Zone heating (kWh)
- Latent Heat - dehumidification [kW]
- Latent Heat – humidification (kW).

The simulation results for the three Case Studies in Design-Builder and WUFI Plus are presented in chapter 5.2.

3.8 Summary

This thesis investigates how traditional and modern building materials might be used to improve hygrothermal comfort in Libyan domestic buildings. For that purpose, the study utilized a methodology combining Case Study monitoring, construction material testing, and hygrothermal performance simulations.

- ***Case Study Monitoring;***

- Three Case Studies were monitored for their hygrothermal and energy performance for 12 months. The collected data from the monitoring was later used to construct and calibrate Case

Study models in Design-Builder and WUFI Plus and to create the weather files needed for the hygrothermal simulations.

- ***Construction Material Testing;***

- Representative construction material samples from Libya were collected and tested for their hygrothermal properties in laboratory setups. The data from material testing was used to create a construction material database for new wall designs in Design-Builder and WUFI Plus. Six different materials and eight wall configurations for each material were suggested.

- ***Hygrothermal Performance Simulations;***

- Computer models of the Case Study Houses were created in Design-Builder and WUFI Plus. To ensure the accuracy of the simulations, the models were calibrated in Design-Builder and WUFI Plus using the collected data from monitoring the Case Studies.
- The suggested wall designs (from Construction Materials Testing) were tested in WUFI 2D to study their hygrothermal behavior and to assess any potential moisture-related issues within these walls over four years.
- The successful wall designs from the hygrothermal behavior assessment in WUFI 2D will be the subjects of the simulations in Design-Builder and WUFI Plus to assess their impact on the hygrothermal comfort and energy performance of the three Case Study Houses.

The results of utilizing the different methodologies are presented in chapters 4 and 5. Chapters 6 and 7 are the discussion and conclusion, respectively.

Chapter Four, Construction Material Testing

4 Construction Material Testing

4.1 Introduction

The objective of this chapter is to investigate the hygrothermal properties of some of the common construction materials of Libya.

This chapter uses laboratory-based experiments to characterise the following materials:

- Limestone - A traditional Libyan building material.
- Hollow Concrete- A modern Libyan building material.
- Sandstone- A traditional Libyan building material.
- Mud Block- A traditional Libyan building material.
- Clay- A traditional Libyan building material.
- Camel's Hair - A traditional Libyan building material.

The following parameters are investigated in this chapter:

- Moisture Buffer Value (MBV), (g/m^2 RH%), [136].
- Water Vapor Diffusion Resistance Factor (μ Value), (-), [135].
- Sorption Isotherm (u), (Kg/Kg), [137].
- Water Absorption Coefficient (Aw), (($Kg/(m^2\sqrt{t})$)), [87].
- Density (ρ), (Kg/m^3), [139].
- Thermal Conductivity (λ), (W/m. K).
- Thermal Diffusivity (α), (m^2/s).
- Specific Heat Capacity (C_p), (KJ/kg. K).

The outcome of this chapter will form a construction material characterisation database for the Libyan context. It will be utilised as a database for the heat and moisture transfer simulations in Chapter 5 of this thesis.

4.2 Experimental Design and Implementation

This subsection presents the results of the hygrothermal tests. The tests methodologies were explained in detail in 3.4.

4.2.1 Determination of Moisture Buffering Capacity (MBV)

4.2.1.1 Test Objective

The objective of the test can be driven by the definition of the moisture buffering property, which is to indicate the amount of moisture uptake or release by a material when exposed to repeated daily variation in relative humidity [64]. Hence, this section aims to determine the moisture buffering values of some common Libyan building materials exposed to indoor air.

The moisture buffering property is beneficial in many ways. It can help moderate extreme indoor relative humidity conditions, improve indoor air quality, enhance the work environment, and reduce heat losses resulting from ventilation, which can help reduce the heating loads in winter [136], [60].

4.2.1.2 Methodology

The Moisture Buffering test was carried out according to the NORDTEST protocol [136]. Details of the methodology, test procedure, and equipment used for the MBV test can be found in section 3.4.1.1. of chapter 3.

4.2.1.3 Test Results and Discussion

The findings of the MBV experiment are shown in Figure 4-1, and Table 4-1 Figure 4-2 shows the classifications of MBV [136].

The findings showed that only the Limestone and Mud Block have "Good" and "Excellent" MBV values, respectively. The results indicate the superiority of Mud block, followed by Limestone, over the rest of the materials in the MBV property. The finding also showed that the Hollow Concrete had the lowest MBV value and is within the "Limited" class range, which is also the case for the Sandstone and Camel's hair samples. Finally, the results showed that the Clay is in the "Moderate" class regarding its MBV value.

The MBV value for the Camel's Hair and Hollow concrete materials was not found in the published research. For the rest of the material (except for the Mud blocks), the results vary from the published research, as can be seen in the results of Makhlouf et al., (2019) [94] (see Table 2.5). The MBV value of the Mud Block in the current study seems to agree with the results from Brambilla & Sangiorgio, (2021) [160] (see Table 2.5).

Table 4-1 MBV Values of the Tested Construction Material Samples

Material	MBV Value (g/m². RH%)	STD
Limestone	1.01	0.52
Hollow Concrete	0.22	0.02
Clay	0.54	0.13
Camel's Hair	0.37	0.04
Mud Block	2.68	0.57
Sandstone	0.30	0.03

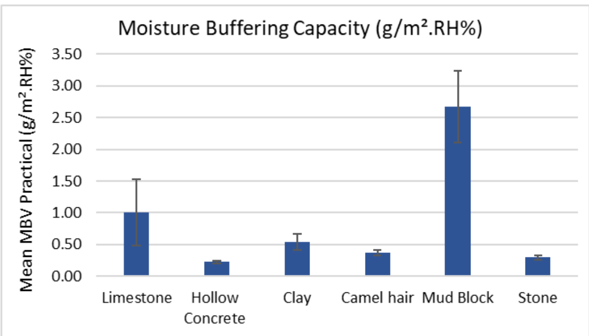


Figure 4-1 MBV Value of the Selected Materials

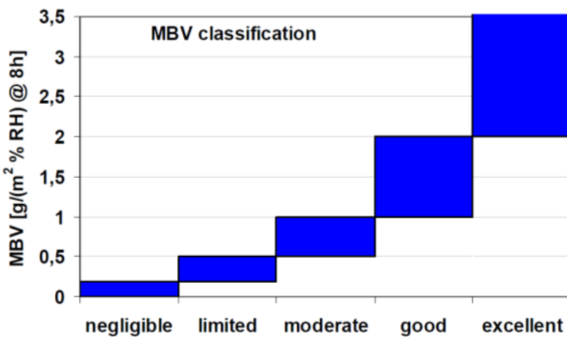


Figure 4-2 MBV Classifications (Rode et al., 2007)

4.2.2 Determination of Water Vapour Diffusion Resistance factor (µ Value), (-)

4.2.2.1 Test Objective

Water Vapour Resistance Factor measures a material's resistance to water passing through its unit surface in time with respect to temperature, dampness, and thickness [161]. Therefore, the test's objective is to investigate the water vapour permeability of the selected construction materials.

4.2.2.2 Methodology

The water vapour permeability is determined according to the British standard BS EN ISO 15272, 2016 [135]. Three test specimens with a minimum area of 100mm² were tested. Testing methodology in detail, equipment used, test procedure, and equations used for the calculations of the µ Value test can be found in chapter 3, section 3.4.1.2.

4.2.2.3 Results

The µ value and Sd value of the construction material samples are shown in Table 4-2, Figures 4-3 and Figures 4-4.

Table 4-2 µ Value and Sd Value of the Selected Construction Materials

Material	µ Value (-)		Sd Value (m)	
	Dry Cup	Wet Cup	Dry Cup	Wet Cup
Limestone	0.1808	0.3891	0.0178	0.0382
Clay	0.3570	0.1951	0.0033	0.0018
Camel Hair	0.1735	0.1492	0.0028	0.0025
Sandstone	1.8463	0.8590	0.0883	0.0411
Hollow Concrete	0.2857	0.2854	0.0086	0.0086
Mud Block	0.3013	0.2780	0.0030	0.0025

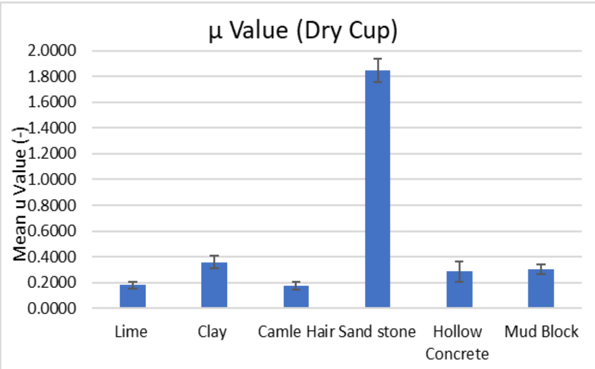


Figure 4-3 Mean µ (-) Value (Dry Cup Test)

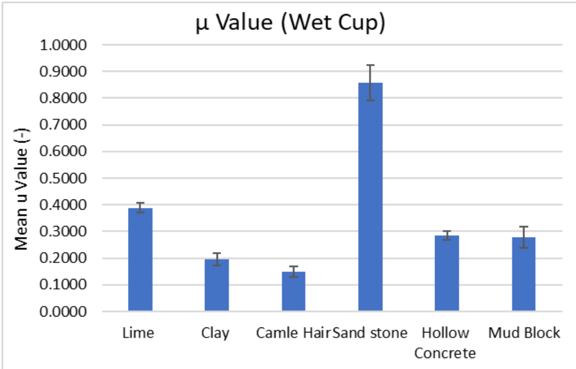


Figure 4-4 Mean µ (-) Value (Wet Cup Test)

The Water Vapour Resistance Factor (µ) measures the material's reluctance to let water vapour pass through. Building elements with poorly designed µ value can be subject to condensation, leading to unhealthy living conditions and building component degradation. The Dry cup test is designed measures the water vapor transmission rate of a material in dry conditions, while the wet cup test measures the water vapor transmission rate in wet conditions. The results of these tests cannot be directly compared because the testing conditions are not the same. [135].

From Table 4-2 above, Figures 4-3 and Figures 4-4, variation in μ value of the construction material samples during both the Wet and Dry cup tests can be observed. Sandstone showed the highest vapour resistance factor during the Dry and Wet cup tests. The lowest water vapour resistance factor was observed for Camel's hair samples during the Dry and Wet cup tests. It was also noted that the μ value of the construction materials obtained by the Dry Cup Test are higher than the values obtained from the Wet Cup Test, except for Limestone, where the results of the Wet cup showed a higher μ value, and for Hollow Concrete where the μ value was similar for both tests. This indicates that Limestone might have lower resistance to moisture flowing outside into the building.

No information was found in the published research regarding the μ value of the Hollow Concrete or the Camel's Hair samples. The results of the μ value of Limestone, Sandstone, and Clay in the current study vary from those in Makhlouf et al., (2019) [94] (see Table 2.5).and Liuzzi et al., (2018)(see Table 2.5). [98]. The results of the Mud Block Dry and Wet Cup tests were in the ranges found in [162] (see Table 2.5).

4.2.3 Determination of Sorption Isotherm (u), (Kg/Kg)

4.2.3.1 Research Objective

This subsection aims to determine the sorption isotherm curves for the moisture sorption and desorption of the selected construction materials specimens. The sorption isotherm curves are fundamental in understanding the moisture transfer mechanism of construction materials.

4.2.3.2 Methodology

The Sorption Isotherm is determined by the climatic chamber method according to the British standard BS EN ISO 12571, (2013). A minimum of three samples, with dimensions of 100X100 mm and true thickness, were dried to constant mass [139]. The methodology in detail is listed in chapter 3, section 3.4.1.3.

4.2.3.3 Test Results

Tables.4-3 to 4-8 Show the mean measured moisture content mass by mass (u), mean measured moisture content volume by volume (w), and mean measured moisture content mass by volume (Ψ). Figures 4-5 to -4-10 show the water adsorption capacity for each of the selected construction material samples in terms of average moisture content mass by mass (u) in percentage. Figures 4-11 and 4-12 show the average measured moisture content for all the construction material samples in terms of Moisture content mass by mass (u).

Table 4-3 Mean Measured Values (u, Ψ, and w) for Clay Samples

RH%@	Sorption			Desorption		
23 °C	u (Kg/Kg)	Ψ (m³/m³)	w (Kg/m³)	u (Kg/Kg)	Ψ (m³/m³)	w (Kg/m³)
0	0.0139	0.029	29.2	0.0106	0.011	11.4
33	0.0163	0.034	34.3	0.0229	0.048	48.1

55	0.0263	0.055	55.2	0.0398	0.084	83.6
75	0.0379	0.080	80.2	0.0443	0.093	93.1
85	0.0620	0.130	130.2	0.0515	0.108	108.1
95	0.0761	0.160	160.0	0.0702	0.127	126.3

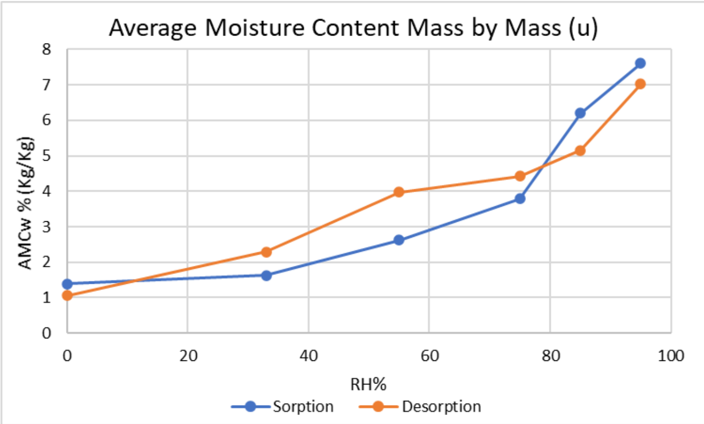


Figure 4-5 Average Moisture Content Mass by Mass for Clay Samples in %

Isotherm Type V for Clay Samples indicating small adsorbent-adsorbate interaction potential and capillary condensation. Also associated with pores from 15-1000Å radius [81], [80].

Table 4-4 Mean Measured Values (u, Ψ, and w) for Hollow Concrete Samples

RH%@	Sorption			Desorption		
23 °C	U (Kg/Kg)	*Ψ* (m³/m³)	w (Kg/m³)	U (Kg/Kg)	*Ψ* (m³/m³)	w (Kg/m³)
0	0.0024	0.004	4.6	0.0020	0.001	1.5
33	0.0040	0.008	7.5	0.0039	0.007	7.4
55	0.0044	0.008	8.2	0.0078	0.015	14.7
75	0.0064	0.012	12.2	0.0079	0.015	14.8
85	0.0093	0.018	17.5	0.0106	0.020	20.1
95	0.0174	0.033	32.8	0.0165	0.027	28.0

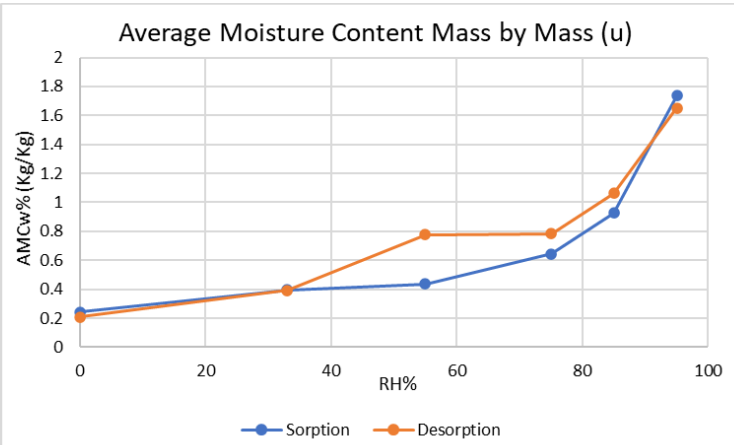


Figure 4-6 Average Moisture Content Mass by Mass for Hollow Concrete Samples in %

Type II isotherm for Hollow Concrete, indicating a non-porosity or macroporosity of the material [81], [80].

Table 4-5 Mean Measured Values (u, Ψ, and w) for Sandstone Samples

RH%@	Sorption			Desorption		
23 °C	U (Kg/Kg)	*Ψ* (m³/m³)	w (Kg/m³)	U (Kg/Kg)	*Ψ* (m³/m³)	w (Kg/m³)
0	0.0004	0.001	0.7	0.0006	0.001	1.1
33	0.0007	0.001	1.3	0.0027	0.005	5.1
55	0.0011	0.002	2.5	0.0037	0.007	7.1

75	0.0013	0.003	2.5	0.0041	0.008	7.9
85	0.0021	0.004	3.9	0.0048	0.009	9.0
95	0.0057	0.011	10.7	0.0053	0.010	10.0

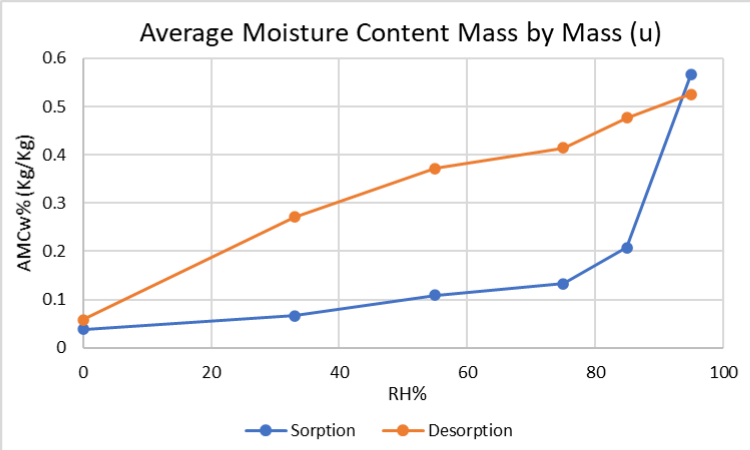


Figure 4-7 Average Moisture Content Mass by Mass for Sandstone Samples in %

Type III Isotherm for Sandston results from non-porosity or macro-porosity of the material with weak moisture interaction [81], [80].

Table 4-6 Mean Measured Values (u, Ψ, and w) for Camel's Hair Samples

RH%@	Sorption			Desorption		
23 °C	U (Kg/Kg)	*Ψ* (m³/m³)	w (Kg/m³)	U (Kg/Kg)	*Ψ* (m³/m³)	w (Kg/m³)
0	0.0312	0.009	8.6	0.0304	0.005	4.7
33	0.0351	0.010	9.6	0.0486	0.013	13.4
55	0.0475	0.013	13.1	0.0714	0.020	19.6
75	0.0621	0.017	17.1	0.0840	0.023	23.1
85	0.0895	0.025	24.6	0.1010	0.028	27.8
95	0.1713	0.047	47.1	0.1456	0.033	33.3

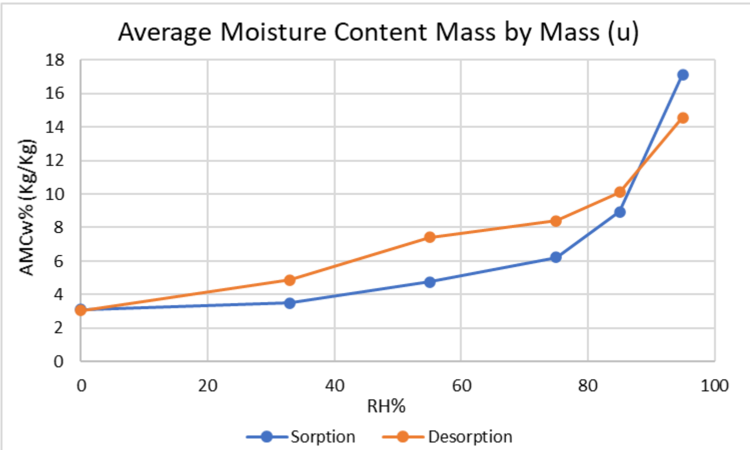


Figure 4-8 Average Moisture Content Mass by Mass for Camel's Hair Samples in %

Type III Isotherm Camel's Hair. Result of non-porosity or macro-porosity of the material with weak moisture interaction [81], [80].

Table 4-7 Mean Measured Values (u, Ψ, and w) for Limestone Samples

RH%@	Sorption			Desorption		
23 °C	U (Kg/Kg)	*Ψ* (m³/m³)	w (Kg/m³)	U (Kg/Kg)	*Ψ* (m³/m³)	w (Kg/m³)
0	0.0007	0.001	1.1	0.0008	0.001	0.8
33	0.0011	0.002	1.7	0.0019	0.001	1.3
55	0.0020	0.003	3.1	0.0034	0.005	5.3

75	0.0029	0.004	4.4	0.0036	0.006	5.6
85	0.0046	0.007	7.1	0.0046	0.007	7.1
95	0.0061	0.009	9.4	0.0062	0.010	9.5

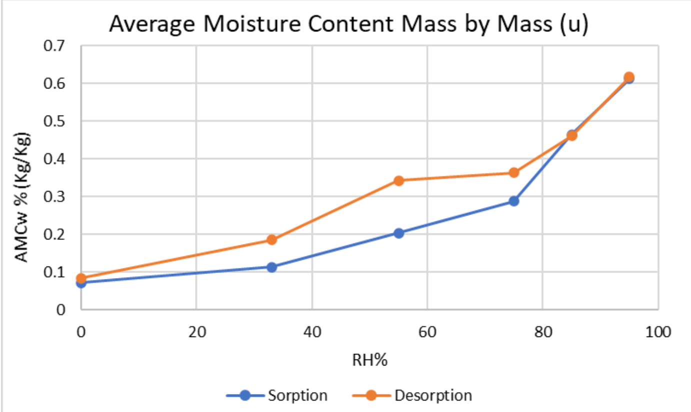


Figure 4-9 Average Moisture Content Mass by Mass for Limestone Samples in %

Type III isotherm for Limestone. Result of non-porosity or macro-porosity of the material with weak moisture interaction [81], [80].

Table 4-8 Mean Measured Values (u, Ψ, and w) for Mud Block Samples

RH%@	Sorption			Desorption		
23 °C	U (Kg/Kg)	*Ψ* (m³/m³)	w (Kg/m³)	U (Kg/Kg)	*Ψ* (m³/m³)	w (Kg/m³)
0	0.0009	0.001	1.4	0.003	0.004	4.03
33	0.0024	0.004	3.6	0.009	0.014	14.05
55	0.0039	0.006	5.8	0.016	0.023	23.43
75	0.0066	0.010	9.8	0.017	0.026	25.92
85	0.0180	0.027	26.7	0.022	0.033	32.73
95	0.0346	0.052	51.5	0.032	0.049	48.39

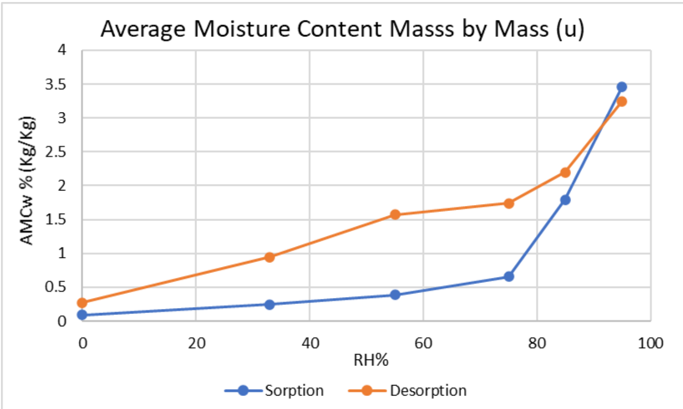


Figure 4-10 Average Moisture Content Mass by Mass for Mud Block Samples in %

Type V Isotherm for Mud Block samples results from small adsorbent-adsorbate interaction potential and capillary condensation. Also associated with pores from 15-1000A radius [81], [80].

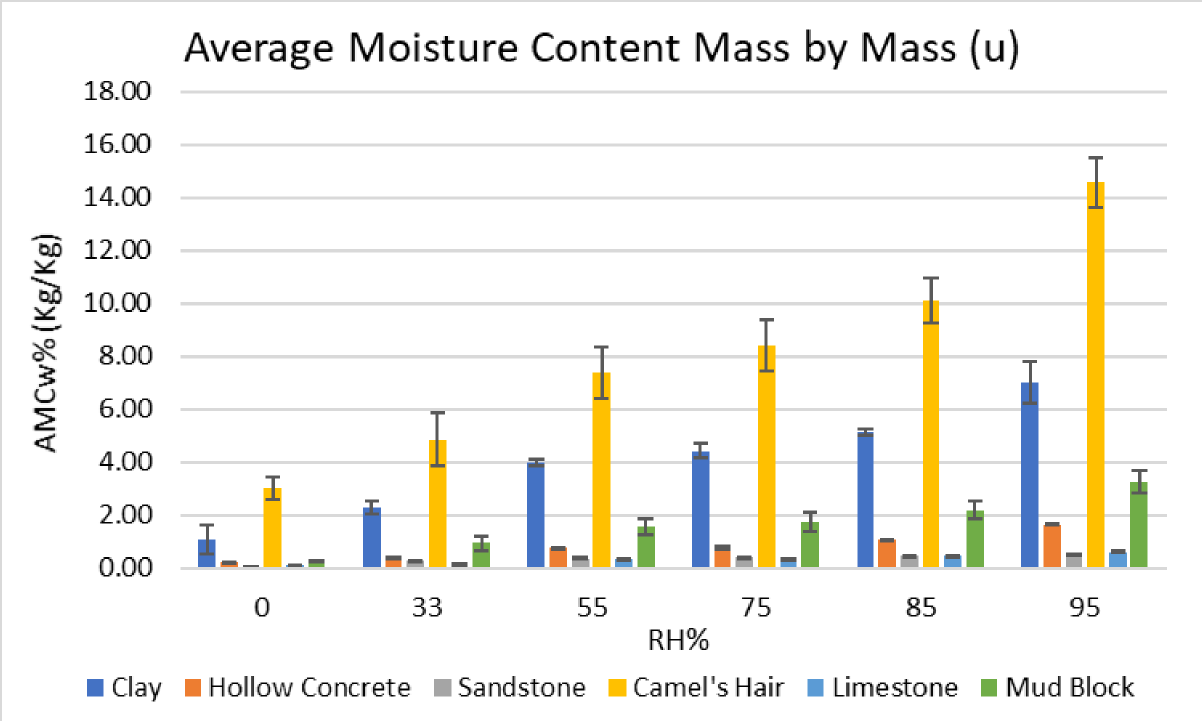


Figure 4-11 Moisture Content Mass by Mass (u)

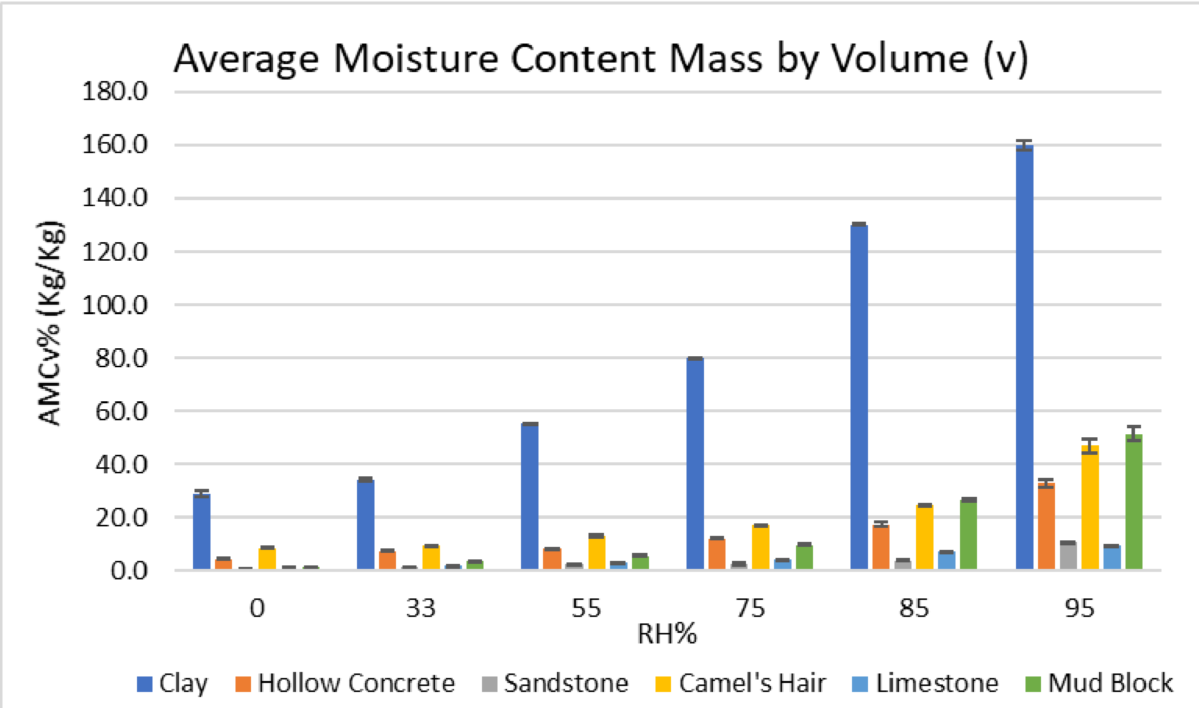


Figure 4-12 Moisture Content Mass by Volume (v)

4.2.3.4 Summary

Sorption isotherm describes the relationship between the equilibrium MC of materials and the ambient RH.

Figure 4-11 showed that, in terms of moisture content mass by mass (u), the Camel's Hair samples are the most hygroscopic compared to the other materials included in this test, with a maximum MC of about 0.17 kg/kg. Clay samples also showed good moisture buffering properties compared to the other materials, with a maximum MC of about 0.07 kg/kg. The maximum MC of the Mud Block samples was about 0.0346 kg/kg, which is superior to Limestone, Sandstone, and Hollow Concrete samples. However, when comparing the moisture content in terms of moisture content mass by volume (MCv) (Figure 4-12), the results showed that the maximum MCv of the Clay samples was around 160 kg/m³, which is the highest MCv observed, followed by Mud Block with about 52 kg/m³ and Camel's Hair with 47.1 kg/m³. This is slightly different from the results of the MCw and might be because of the difference in the densities of the measured materials.

The term "Hysteresis" refers to the difference in the MC between adsorption and desorption. Hysteresis was observed for all materials included in this test. The highest difference between sorption and desorption was observed in the Sandstone samples, peaking at around 75% RH (Figure 4-10). This can be because of mesoporosity and/or an adsorbent-adsorbate interaction. It might also indicate the Sandstone's slow response to the changes in ambient RH.

A relatively high Hysteresis was observed for Mud Block samples and is accruing between 15-95% RH. The observed Hysteresis was relatively limited for the remaining material samples and usually accrued between 33% and 75% RH. It was also noted that almost all the materials were able to release the absorbed moisture content to the surrounding environment.

4.2.4 Determination of Water Absorption Coefficient (Aw), ((Kg/(m²√t))

4.2.4.1 Test Objective

This test aims to quantify the liquid water diffusivity of the selected construction materials samples, which is beneficial for understanding and measuring the moisture absorption rate of building materials.

4.2.4.2 Methodology

The water absorption coefficient for the selected construction materials is determined following the British standard BS EN ISO 15148, (2016). Methodology, equipment, test procedure, and calculations are detailed in section 3.4.1.4., chapter 3.

4.2.4.3 Test results

This section presents the results of the Water Adsorption Coefficient test (A value). The test was conducted for the following materials: Limestone, Hollow Concrete, Sandstone, Camel's Hair, Clay, and Mud Block. However, Clay and Mud Block tests had to be determined as the materials started dissolving in water after 5 minutes for the Mud Block and 20 minutes for the Clay. For the remaining materials, Figure 4-13 to Figure 4-16 presents the results of Δm against $\sqrt{t}$, and Figure 4-17 presents the Aw,24 for the tested materials.

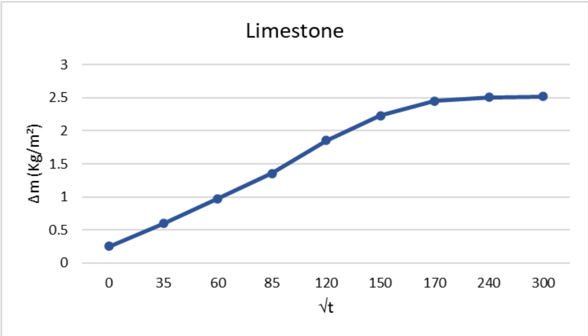


Figure 4-13 Δm Against √t (Limestone)

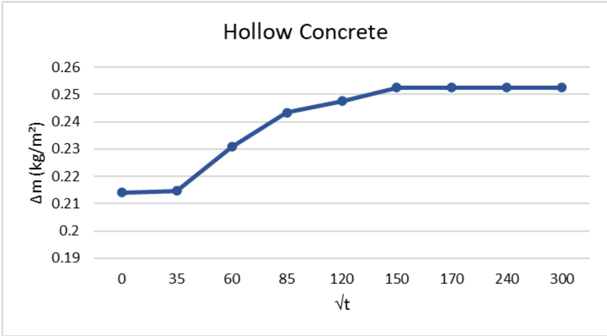


Figure 4-14 Δm Against √t (Hollow Concrete)

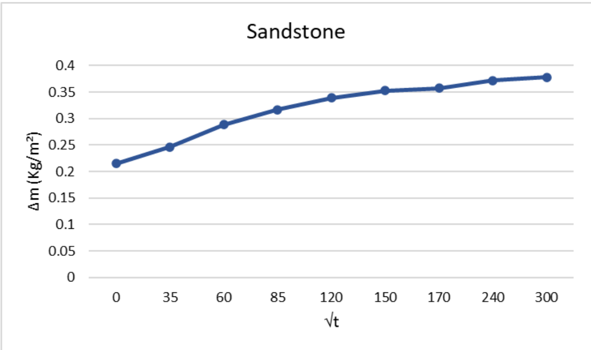


Figure 4-15 Δm Against √t S(Sandstone)

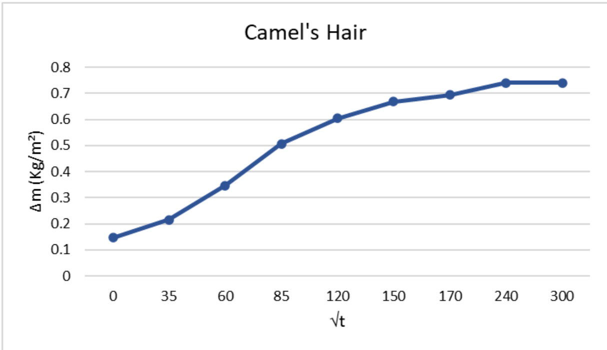


Figure 4-16 Δm Against √t (Camel's Hair)

The results of plotting Δm against $\sqrt{t}$ shows that all the material gave a curve, and therefore, equation 3.13 was applied for Limestone, Hollow Concrete, Camel's Hair, and Sandstone samples. The results are shown in the figure below.

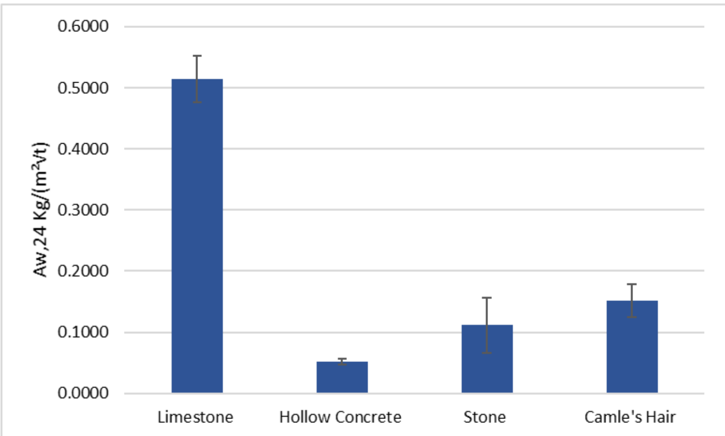


Figure 4-17 Compare Different Aw values of the Construction Material Samples obtained from the Aw Test

The Water Absorption Coefficient (Aw value) measures the moisture absorption rate of building materials. It indicates "how many kg of water per hour one square meter of material can absorb through capillary action" [163]. In general, and especially in climates with heavy rainfall, materials with a low A value are better suited for external walls due to their higher resistance to water flow.

The figure above shows the results of measuring the A value of the selected construction material samples. The test was only completed for four materials, as both Clay and Mud Block samples started dissolving in water after just 20 minutes from the start, indicating that these two materials, the Clay, and Mud Block, have low water resistance. This means that these two materials, Clay and Mud Block, might not be suitable for use in external walls, especially in areas with high humidity and rainfall and that these two material might require some kind if protection form moisture and rainfall. Some of these measures include, applying waterproof coating, using moisture resistance mortar, as well as providing adequate drainage and ventilation to prevent moisture form accumulating. While some of these measures can protect Clay and Mud Block form high humidity and rain, they might also have an impact on the materials ability to absorb and releases moisture, which can affect their moisture buffering capacity. Similarly, using a moisture-resistant mortar may reduce the airflow through the walls, which can affect their ventilation and drying capacity. Clay and mud blocks have been used in construction for centuries. In the past, traditional builders relied on local knowledge and experience to protect these materials from rain and moisture. Some common techniques used in the past include; using sloping roofs with large overhangs to protect the walls from direct rain exposure, Surface treatments such as lime plaster, mud plaster, or paint were applied to the exterior walls to provide additional protection from rain and the proper site selection where in some cases, builders selected building sites that were naturally well-drained or used techniques such as building on a raised platform to avoid moisture damage [164]. It is worth noting however, that the protective measures used in the past may not be sufficient for modern construction standards, and additional protection may be necessary to prevent moisture damage. Therefore, further research is recommended on the use of protective measures for Clay and Mud Block materials before any real-life application of those materials.

For the remaining materials, the results showed that Limestone had the highest A value, with about 0.5140(($Kg/(m^2\sqrt{t})$)), followed by Camel's Hair, 0.1513 (($Kg/(m^2\sqrt{t})$)), and Sandstone with about 0.1115 (($Kg/(m^2\sqrt{t})$)), and Hollow Concrete having the lowest A value with about 0.05151 (($Kg/(m^2\sqrt{t})$)). The results indicate the superiority of the Hollow Concrete, in terms of Water absorption Coefficient, over the remaining materials included in this study.

4.2.5 Density (kg/m^3)

Density is essential in calculating the hygrothermal properties of construction materials and is crucial for the hygrothermal simulations. For the calculations of hygrothermal properties of the construction material samples, it is required first to measure and calculate the dry density of those materials [139], using the formula below:

$$\rho_0 = \frac{m_0}{V} \qquad (1.4.)$$

Where: m_0 is the mass of the dry specimen, and v is the volume of the dry specimen.

4.2.5.1 Test Results

Results of measuring the dry density (ρ_0) of the test specimens are presented in the Table and the figure below.

Table 4-9 Dry Density of the Selected Construction Material Samples

Material	Volume (m³)	Mass (Kg)	Density (Kg/m³)
Limestone	0.0011±0.0	1.6142±0.1	1538± 80
Hollow Concrete	0.0008±0.0	1.4302±0.1	1889± 71
Clay	0.0001±0.0	0.1766±0.03	2100± 133
Camel Hair	0.0002±0.0	0.0631±0.005	275± 14
Sandstone	0.0005±0.0	0.9380±0.014	1897± 59
Mud Block	0.0013±0.0	1.8888±0.2	1489± 29

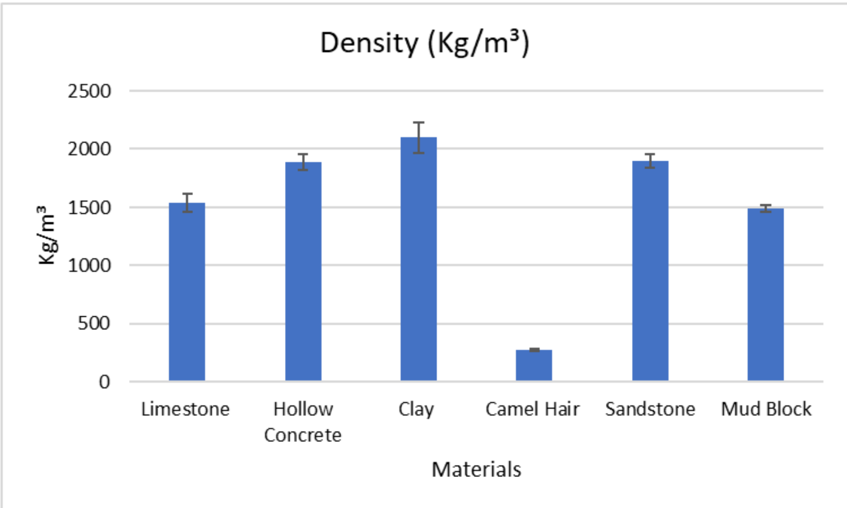


Figure 4-18 Dry Density Comparison Between the Selected Construction Material Samples

The Table above shows the results of calculating the dry density of the selected construction material samples. The results showed that Clay samples have the highest density. The table also showed that the Hollow Concrete and Sandstone samples have similar densities with 1889 (Kg/m³) and 1897 (Kg/m³), respectively. The Camel's hair samples had the lowest density, as seen from the table.

The findings showed that the density of the Sandstone is in line with the results of Makhlouf et al., (2019) (see Table 2.5). Mud Block shows a lower density than the values from Cagnon et al., (2014) (see Table 2.5). The density of Clay samples is higher than those found in Liuzzi et al., (2018) (see Table 2.5). There was no data found regarding the density of Camel's Hair.

4.2.6 Determination of Thermal Conductivity, Diffusivity, and Specific Heat Capacity

This section aims to determine the Thermal Conductivity, Thermal Diffusivity, and Specific Heat Capacity of the selected construction material samples.

4.2.6.1 Methodology

The methodology details for measuring the thermal properties of the material samples can be found in chapter 3, section 3.4.1.6.

4.2.6.2 Results

The results of the thermal tests are presented in Table 4-10 below in terms of average values and standard deviations. Table 4-11 presents a comparison between the finding of this study compared to the values available from published data and online sources.

Table 4-10 Results of Measuring the Thermal Properties of the Selected Materials

Material	Thermal Conductivity (λ)(W/m. K)	Volumetric Heat Capacity (C vol) (m³.k)	Thermal Diffusivity (α) (m²/s)	Density (ρ) (Kg/m³)	Specific Heat Capacity (C_p) (KJ/kg. K)
Limestone	0.45(±0.0)	1.44(±0.0)	0.32(±0.01)	1538	938
Camel Hair	0.09(±0.0)	1.32(±0.0)	0.40(±0.01)	275	4804
Sandstone	1.18(±0.0)	1.55(±0.0)	0.76 (±0.0)	1897	814
Hollow Concrete	0.94(±0.0)	1.66(±0.0)	0.56(±0.02)	1889	881
Mud Block	0.72(±0.0)	1.71(±0.0)	0.42(±0.0)	1489	1150
Clay	0.68(±0.0)	2.03(±0.0)	0.33(±0.0)	2100	970

The Table above shows that Camel's Hair had the lowest thermal Conductivity and the highest heat capacity. The table also showed that Limestone has a relatively low thermal conductivity and relatively high specific heat capacity compared to the other materials included in the test. This indicates high thermal resistance and mass; both properties are desirable in building materials. Mud Blocks and Clay showed a potential for relatively good thermal performance, as those two materials' Thermal Conductivity and specific heat capacity showed better performance than the Sandstone and Hollow Concrete samples.

Table 4-11 Comparison Between Published Hygrothermal Data and The Findings of the Current Study

Material	Ref	Hygrothermal properties						
		Bulk Density (kg/m³)	**Porosity** (m³/ m³)	**Heat Capacity** (J/kgK)	**Thermal Conductivity** (W/mK)	**Vapour Resistance** (-)	**MBV** (g/m² RH%)	**Water Absorption Coefficient** ((Kg/(m²√t))
Limestone	[88]	2500	0.05	840	0.7	770	-	-
	[89]	2440	0.12	850	2.25	140	-	-
	[90]	2650	0.035	2600	3	35.7	-	-
	Current study	**1538**	**-**	**938**	**0.45**	**18**	**1.01**	**0.5140**
Camel's Hair	**Current study**	**275**	**-**	**-**	**-**	**17**	**0.37**	**0.1513**
Sandstone	[88]	2268	0.14	828	2.503	87	-	-
	[89]	2224	0.17	771	1.684	73	-	-
	[90]	2300	0.05	850	2.3	70	-	-
	Current study	**1897**	**-**	**814**	**1.18**	**184**	**0.3**	**0.1115**
Hollow Concrete	[88]	2322	0.15	850	1.7	192	-	-
	[89]	2315	0.1296	800	0.733	182.3	-	-
	[90]	2300	0.18	850	1.6	197	-	-
	Current study	**1889**	**-**	**881**	**0.94**	**28**	**0.22**	**0.05151**
Mud Block	[90]	1514	0.42	1000	0.59	11	-	-
	Current study	**1489**	**-**	**1150**	**0.72**	**30**	**2.68**	**-**
Clay	[88]	1935	0.217	800	0.495	137.8	-	-
	[89]	1821	0.333	800	0.516	68.5	-	-
	[90]	1267	0.517	850	0.288	50	-	-
	Current study	**2100**	**-**	**970**	**0.68**	**35**	**0.54**	**-**

The table above showed the results of the hygrothermal tests in comparison to the published hygrothermal material data. There are variations in the hygrothermal properties obtained from the online database, as can be seen from the table. At the time of writing this thesis, there was no data available that is directly related to the key material of Libya presented in this research.

In terms of density, the table showed that Limestone had a lower value than those in the online databases. This was also the case for Sandstone, and Hollow Concrete, where both of these materials showed a slightly lower value compared to the online database. There was no information regarding Camel's hair properties in the online materials database.

For the Heat Capacity property, the table showed that the values obtained from this research for Limestone, Sandstone and Hollow Concrete are within the range of the value found in the online databases. For Mud Block and Clay, the table showed that the values obtained from this research are slightly higher compared to the online material databases. There was no available data for Camel's Hair Capacity in the online sources.

For Thermal Conductivity, there was no data available for Camel's Hair. For the remaining materials, the Thermal Conductivity seems in range with the online databases.

For the Water Vapour Diffusion Resistance Factor, the table showed variation between the results obtained from this research and those from the online databases. There was no information on the MBV or the Water Absorption Coefficient properties for the selected materials in the online databases.

To conclude, the table showed that for the selected materials, the values obtained from the experiment vary from those obtained from the online databases. However, in most cases, those values are within the range of the online database values. This comparison further highlights the importance of carrying out experimental categorization of materials as was mentioned before.

4.3 Chapter Summary

This chapter covered the experimental investigation of the hygrothermal properties of Libyan building materials.

The tested materials included Limestone, Hollow Concrete, Clay, Mud Blocks, Sandstone, and Camel's Hair. The selected materials were tested for the following properties: Moisture Buffer Value ((MBV), (g/m² RH%)), Water Vapor Diffusion Resistance Factor ((µ Value), (-)), Sorption Isotherm ((u), (Kg/Kg)), Water Absorption Coefficient ((Aw), (Kg/(m²√t)), Density ((ρ), (Kg/m³)), Thermal Conductivity ((λ), (W/m. K)), Thermal Diffusivity ((α), (m²/s)), Specific Heat Capacity ((C_p), (KJ/kg. K)). The outcome of this chapter will form the database for the hygrothermal simulations in Design-Builder and WUFI Plus in the next chapter.

- The Moisture Buffer value (MBV) is an important material property, especially for climates with relative humidity cycles swing. The results of the MBV test showed that Limestone had a moderate MBV Value. The lowest MBV value was observed for Hollow Concrete and is within the "negligible" range. The findings showed that Clay, Camel's Hair, and Sandstone were classified as "limited" in the MBV value.
- Despite its "excellent" MBV value, Mud Block showed poor resistance to water absorption, which was also the case for Clay samples. Poor water resistance could mean that these materials (Mud Block and Clay) might be vulnerable to rainfall and require some protection (such as a rain

screen) to withstand the extreme climate conditions. For the remaining materials, the highest Aw value was observed for Limestone, followed by Camel's Hair. The lowest Aw value was observed for Hollow Concrete Samples, indicating the superiority of Limestone over the remaining materials in terms of its Water absorption Coefficient (Aw) property.

- In terms of the Water Vapour Diffusion Resistance Factor (μ value), variations in the Dry and Wet Cup results were observed for all materials included in the test. It was noticed that Sandstone samples had the highest μ value during both the Dry and Wet Cup tests. The lowest μ value during the Dry and Wet Cup tests was seen in the Camel's Hair samples. The results also showed that the μ values obtained from the Wet Cup Test are lower than the Dry Cup, except for Limestone, where the results of the Wet cup showed a higher μ value and Hollow Concrete, where the μ value was similar for both tests. Furthermore, the observed μ value for the Limestone (during the Dry Cup test) was relatively low compared to the other materials (except for Camel's Hair).
- For the Sorption Isotherm test, the highest Hysteresis was seen in the Sandstone samples peaking at around 75% RH. The results also showed that in terms of moisture content mass by mass (MCw), Camel's Hair samples were the most hygroscopic compared to the other material included in the test. A good moisture buffer property was also noted for the Clay samples compared to the other materials. When comparing the results in terms of moisture content mass by volume, however, the results showed that Clay followed by Mud Block had the highest adsorption capacities, indicating that the density of those materials might be the factor influencing their practical hygroscopic capacity.
- Finally, the thermal investigation showed that Limestone had relatively low Thermal Conductivity and relatively high specific heat capacity compared to the other materials included in the tests. The results also showed that Mud blocks also had low Thermal Conductivity and relatively high Specific Heat Capacity, indicating higher thermal mass and higher thermal resistance than Hollow Concrete and Sandstone samples. Clay shows relativity low thermal conductivity and specific heat capacity similar to Limestone samples. Camel's Hair, which is to be used as insulation material, was found to have the lowest density and thermal Conductivity, while its specific heat capacity was the highest among the measured materials.

The findings of this chapter indicate that Limestone, Mud Block, Camel's hair and Clay have overall good hygrothermal properties compared to Sandstone and Hollow Concrete. Hence those materials will be used to design new walls, which will be tested in Design-Builder and WUFI Plus in the next chapter.

In conclusion, and based on the experimental investigation of the hygrothermal properties of Libyan building materials, Limestone, Mud Block, Camel's Hair, and Clay demonstrated good hygrothermal properties compared to Sandstone and Hollow Concrete. Limestone had a moderate Moisture Buffer Value, relatively low Thermal Conductivity, and relatively high Specific Heat Capacity. Mud Block showed poor resistance to water absorption despite its excellent Moisture Buffer Value. Camel's Hair had the lowest density and thermal Conductivity, and its specific heat capacity was the highest among the measured materials. Clay demonstrated relatively low thermal conductivity and specific heat capacity similar to Limestone samples. Sandstone and Hollow Concrete exhibited inferior hygrothermal properties compared to the other materials.

Chapter Five, Building Simulations

5 Building Simulations

The objective of this chapter is to numerically evaluate the impact that changing the envelope materials might have on the hygrothermal performance of the Case Study Houses and to present a new wall system for designing contemporary houses in Libya using locally available building materials.

The hygrothermal simulations will be performed using two building simulation tools: Design-Builder and WUFI Plus. To ensure accurate results, the Case Study building models were calibrated using real-time monitoring data in both Design-Builder and WUFI Plus (see 5.1).

Traditional and modern building materials from Libya were tested for their hygrothermal properties in chapter 4. The results from chapter 4 were used to design new walls for the Libyan contemporary domestic buildings. The hygrothermal behaviour of the proposed walls will be tested in WUFI 2D before being tested in the simulation tools (Design-Builder and WUFI Plus) to evaluate their potential impact on hygrothermal comfort and energy performance of the Case Study Houses (see 5.2).

The parameters used to evaluate the impact of changing the wall materials are the indoor relative Humidity (RH%), air temperature °C, radiant temperature °C, and operative temperature °C. The hygrothermal comfort of the Case Study Houses will be assessed using Fanger's MPV/PPD steady-state heat balance models [165].

5.1 Calibration of Building Models

This section presents the calibration results of the three Case Study Houses. The calibration methodology is listed in detail in chapter 3, section 3.6.1. More information regarding the calibration of building models is in chapter 2, section 2.8.

5.1.1 Calibration Methodology

This study uses a simplified calibration methodology adopted from published research (see 3.6.1. and 2.8). The adopted methodology consists of the following five -steps (see Table 2-7):

- **Step One**, Model Preparation, adapted from the following studies: [166], [108], [109], [118] [119], [121], [122], [123], [167].
- **Step Two**, Parameter Identification (as in [118]).
- **Step Three,** Sensitivity Analysis (adopted from [166], [118] and [146]).
- **Step Four**, Adjustment of Parameters (as in [108] and [118]).
- **Step Five**, Analysis of the Results (as in all the reviewed studies, see step one).

5.1.2 Building Models Calibration Results in Design-Builder and WUFI Plus

5.1.2.1 Calibration Results of Case Study House 1

This section presents the Calibration results of Case Study House 1.

- ***Step One; Data Collection***

The input data for the Base Model of Case Study House 1 are shown in Table 5-1. The envelope details of the Base Model are presented in Table 5-2.

Table 5-1 Input Parameters for the Base Model of Case Study House 1

Parameter	Details
Building location	Latitude: 32.70, longitude 13.08, elevation (m) 63.0
Orientation (^{o})	North Axis Angle: 80
Area (²m)	92
WWR (%)	20
Glazing type	Uninsulated glazing with no solar protection
Construction Materials	Wall: Limestone+ Cement Plaster Roof: Reinforced Concrete
Envelope thickness (mm)	Wall: 250. Roof: 250
Lighting Target Illuminance (lux)	100
Equipment power density (W/²m)	2.16
Occupancy template	Married_ Couple_ Two_ Children
Occupancy density (people/m^2)	0.0155
Number of occupants	4
HVAC Type	Split+ Separate Mechanical Ventilation
Operation Schedule	07:00-23:00

Table 5-2 Envelope Details of the Base Model of Case Study House 1 [6].

Envelope details	Material	Thickness (mm)	λ (W/m-K)	ρ (kg/³m)	Cρ (J/Kg-K)
Wall	Cement plaster	25	1.4	600	1000
U-Value (W/m²-K) = 2.8	Limestone	200	1.5	2180	720
	Cement plaster	25	1.4	600	1000
Roof	Floor tiles	10	0.6	500	750
U-Value (W/m²-K) =	Cement mortar	20	1.4	2100	650
3.46**3**	Reinforced concrete	200	1.4	2100	653
	Cement plaster	25	1.4	600	1000

- ***Step two; Parameter Identification***

By analysing the heat balance reports of the Base Case Model of Case Study House 1 from Design-Builder and WUFI Plus, the most influencing parameters are listed in Table 5-3 below (see 3.6.1) for more details).

Table 5-3 Heat Gain Components of Case Study Houses 1

Component	Heat Gains			
	Summer		Winter	
	[W/²m]	%	[W/²m]	%
HVAC	2.1	35	6.3	43
Envelope	1.7	28	6.1	41
Equipment	0.8	14	1.1	8
Window	0.8	14	0.5	4
Infiltration	0.5	9	0.7	4

Table 5-3 showed that for Case Study House 1, the key parameters are, in order, envelope, equipment/windows with infiltration having the most negligible impact on the demand placed on the HVAC system. The parameters listed in Table 5-3 will receive more attention during the sensitivity analysis in step 3.

- ***Step Three; Sensitivity Analysis***

The sensitivity analysis will be performed by changing the input values of the parameters included in Table 5-3 above, starting with the parameters that ranked highest in the table. The variables related to each parameter, which will undergo the sensitivity analysis, were listed in Table 3-19 in the methodology chapter.

Using the Influence coefficient (IC%) from equation (3.19), the sensitivity analysis results for electricity consumption and indoor temperature of Case Study House 1 are presented in Table 5-4 below.

Where: *IPBC* = Base Case input, *IPBC1* = Case 1 input, *ΔIP= IPBC-IPBC1*, *OPBC* = Base Case output, *OPBC1* = Case1 output, *ΔOP= OPBC-OPBC1*, IC= Influence Coefficient (Percentage change in the output for every 1% variation in the input).

Where:

- Base Case is the Base Case Model with the original input parameters.
- Case 1 Model is the base Case Model after varying any of the parameters under investigation.

Table 5-4 Influence Coefficient (IC%) for Electricity and Indoor Temperature of Case Study House 1

Electricity Consumption IC%								
Base Case input (winter)		**IPBC**	**IPBC1**	**ΔIP**	**OPBC (kWh)**	**OPBC1 (kWh)**	**ΔOP (kWh)**	**IC%**
HVAC	CoP	2.25	1.85	0.4	303.8	369.5	-65.7	-1.22
Wall (W/m²-K)	U-value	2.8	1	1.8	303.8	216.4	87.4	0.45
Windows	WWR%	10%	40%	-30.0%	303.8	295.7	8.1	-0.01
	U-value	5.78	1.96	3.82	303.8	301.47	2.33	0.01
Equipment (W/²m)	Power density	2.16	16	-13.84	303.8	274.1	29.7	-0.02
Infiltration (ac/h)	Constant rate	1.5	3	1.5	303.8	882.4	-578.6	0.14
Base Case input (Summer)		**IPBC**	**IPBC1**	**ΔIP**	**OPBC (kWh)**	**OPBC1 (kWh)**	**ΔOP (kWh)**	**IC%**
HVAC	CoP	1.8	1	0.8	357.2	803.7	-446.5	-2.81
Wall (W/m²-K)	U-value	2.8	1	1.8	357.2	115.4	241.8	1.05
Windows	WWR%	10%	40%	-30%	357.2	435.9	-78.7	0.07
	U-value	5.78	1.96	3.82	357.2	351.3	5.9	0.03
Equipment (W/²m)	Power density	2.16	8	-5.84	357.2	368	-10.8	0.01
Infiltration (ac/h)	Constant rate	1.5	3	1.5	357.2	138.5	218.7	0.77
Indoor Temperature IC%								
Base Case input (winter)		**IPBC**	**IPBC1**	**ΔIP**	**OPBC (°C)**	**OPBC1 (°C)**	**ΔOP (°C)**	**IC%**

HVAC	Setpoint	18.00	21	-3	15.77	15.95	-0.18	0.068
	Setback	12	14	-2	15.77	15.97	-0.2	0.076
Wall (W/m²-K)	U-value	2.8	1.8	1	15.77	15.53	0.24	0.043
Windows	WWR%	10	40	-30	15.77	15.94	-0.17	0.005
	U-value	5.778	1.96	3.82	15.77	15.64	0.13	0.012
Infiltration (ac/h)	Constant rate	1.5	3	1.5	15.77	16.07	-0.3	0.053
Base Case input (Summer)		**IPBC**	**IPBC1**	**ΔIP**	**OPBC (°C)**	**OPBC1 (°C)**	**ΔOP (°C)**	**IC%**
HVAC	setpoint	25.00	23	2	29.55	29.05	0.5	0.212
	Setback	28	25	3	29.55	29.55	0	0.000
Wall (W/m²-K)	U-value	2.8	1.8	1	29.55	28.87	0.68	0.064
Windows	WWR%	10	40	-30	29.55	29.99	-0.44	0.007
	U-value	5.78	1.96	3.82	29.55	29.51	0.04	0.002
Infiltration (ac/h)	Constant rate	1.5	3	1.5	29.55	29.66	-0.11	0.072

Tables 5-4 show the IC% calculations for the most influencing indoor temperature and electricity consumption parameters of Case Study House 1.

The table showed that the most influencing electricity consumption parameter was the CoP of the HVAC System. The calculations showed that for every ±1% variation in the CoP, there would be around ±1.2% and ±2.8% variation in the cooling and heating loads, respectively. The table also showed that the most influencing parameter for the indoor temperature was the HVAC system's Setpoint and setback, where every ±1% variation in the setpoint and setback points would result in around ±0.07% and ±0.08% variation in the indoor temperature. It should be noted that this study used the same HVAC setpoint and setback during the same period for both, the temperature and the energy calibration.

Table 5-5 below are the influencing parameters ranked, in terms of IC%, from highest to lowest for Case Study House 1.

Table 5-5 Building Parameters Rankings in Terms of IC%

Energy Parameters					
Winter			**Summer**		
No.	**Parameter**	**IC% per ±1% IP**	**No.**	**Parameter**	**IC% per ±1% IP**
1	HVAC CoP	1.216	1	HVAC CoP	2.813
2	Wall U-value	0.448	2	Wall U-value	1.053
3	Infiltration	0.136	3	Infiltration	0.765
Temperature parameters					
1	HVAC Setback	0.076	1	HVAC Setpoint	0.212
2	HVAC Setpoint	0.068	2	Infiltration	0.072
3	Infiltration	0.053	3	Wall U-value	0.064
4	Wall U-value	0.043			

Table 5-5 above shows the ranking of parameters with the most influence on energy consumption and indoor temperature for Case Study House 1. For the three Case Studies, the HVAC setpoints are used to control the internal temperature of a building. Once these setpoints are fixed, the HVAC system will adjust its energy consumption to achieve the desired HVAC setting. In other words, the HVAC system will use more or less energy depending on the difference between the desired temperature and the actual temperature in the building. The energy consumption is then calibrated through other variable, such as those showed in the Tabel above. These parameters will be refined and adjusted in the next step until the building models' energy consumption and indoor temperature are calibrated.

- ***Step Four: Adjusting Input Parameters***

After a few simulation runs (see 3.6.1 for methodology details), Case Study House 1 was calibrated.

- ***Step Five, Analysis of the Results***

The energy calibration results in Design-Builder and WUFI Plus of Case Study House 1 are in Figure 5-1 below. Calibration results of indoor temperature and relative humidity for Case Study House 1 are in Tables 5-6, 5-7 and Figure 5-2 below. The performance gap between the measured and simulated energy consumption, in terms of hourly MBE% and Hourly Cv (RMSE)%, For Case Study House 1 is presented in Table 5-8.

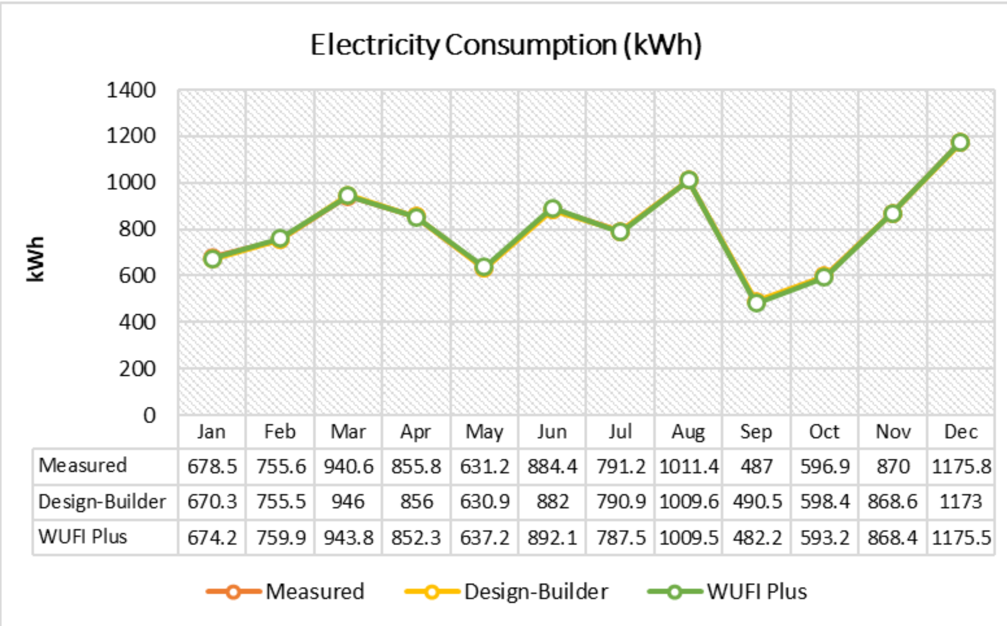


Figure 5-1 Electricity Calibration Results for Case Study House-1 in Design Builder and WUFI Plus

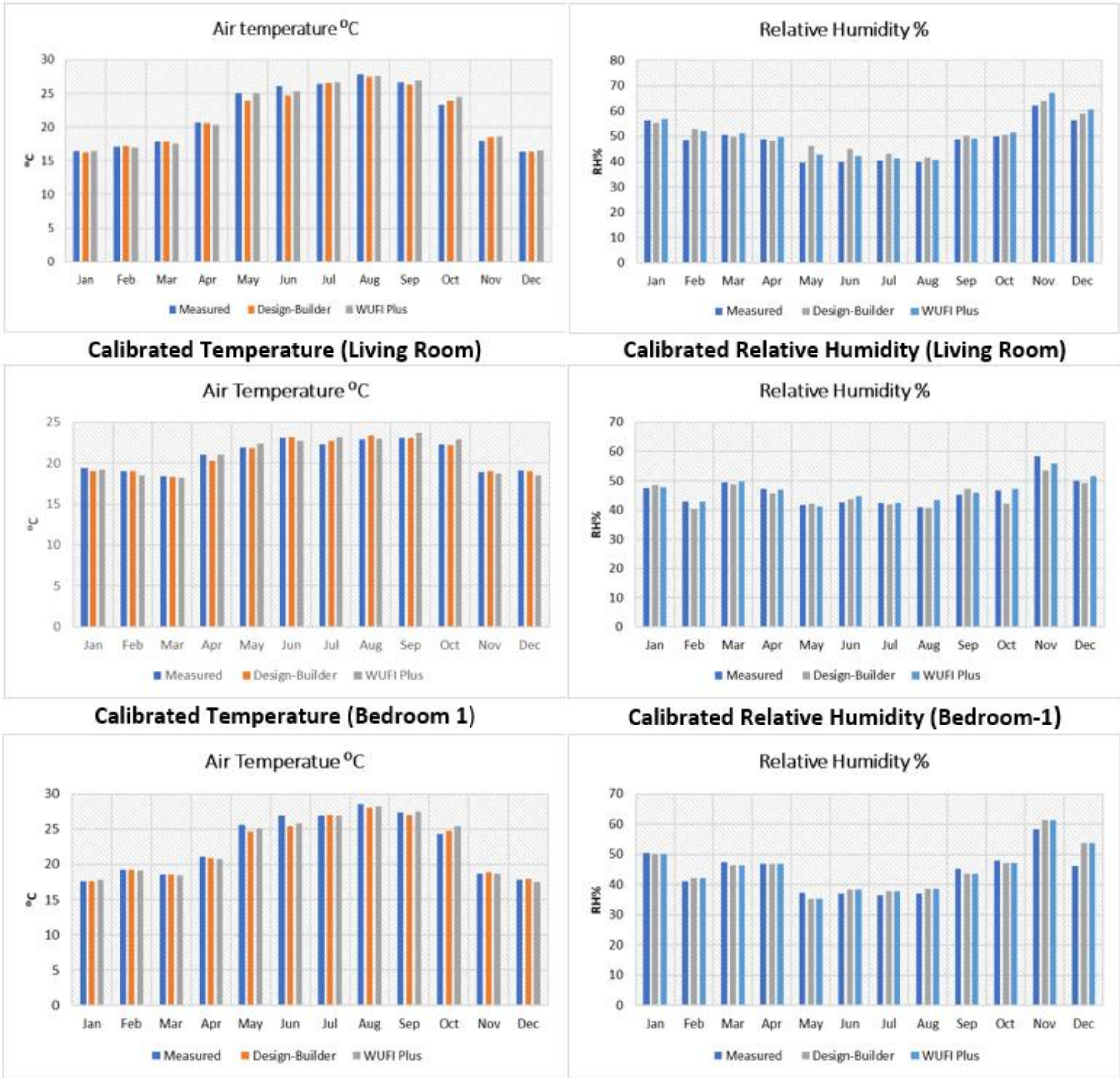
Table 5-6 Temperature Calibration Results for Case Study House-1 in Design-Builder and WUFI Plus

Time	Living Room °C			Bedroom-1 °C			Bedroom-2 °C		
	Measured	Design Builder	WUFI Plus	Measured	Design Builder	WUFI Plus	Measured	Design Builder	WUFI Plus
Jan	16.4	16.2	16.4	19.4	19	19.2	17.6	17.6	17.8
Feb	17.1	17.2	17	19	19	18.5	19.2	19.2	19.1
Mar	17.9	17.8	17.5	18.4	18.3	18.2	18.6	18.6	18.5
Apr	20.7	20.6	20.3	21	20.3	21	21.1	20.9	20.7
May	25	23.9	25	21.9	21.8	22.4	25.6	24.7	25.1
Jun	26.1	24.7	25.3	23.1	23.2	22.7	26.9	25.4	25.8
Jul	26.4	26.5	26.6	22.3	22.7	23.2	26.9	27	26.9
Aug	27.8	27.5	27.6	22.9	23.4	23	28.5	28	28.2

Sep	26.6	26.3	26.9	23.1	23.1	23.7	27.4	27	27.5
Oct	23.3	23.9	24.5	22.3	22.2	22.9	24.3	24.8	25.4
Nov	18	18.5	18.6	18.9	19	18.8	18.7	18.9	18.7
Dec	16.3	16.3	16.6	19.1	19	18.5	17.8	17.9	17.5

Table 5-7 RH Calibration Results for Case Study House-1 in Design-Builder and WUFI Plus

Time	Living Room RH%			Bedroom-1 RH%			Bedroom-2 RH%		
	Measured	Design Builder	WUFI Plus	Measured	Design Builder	WUFI Plus	Measured	Design Builder	WUFI Plus
Jan	56.2	55.3	56.8	47.5	48.5	47.8	50.5	50.2	50.2
Feb	48.4	52.8	51.9	42.8	40.3	42.8	41	42.1	42.1
Mar	50.7	49.6	51.2	49.6	48.8	49.7	47.4	46.3	46.3
Apr	48.7	48.1	49.8	47.3	45.7	46.9	46.9	46.8	46.8
May	39.6	46.2	42.7	41.7	42.1	41.2	37.2	35.3	35.3
Jun	39.9	45.1	42.2	42.7	43.6	44.7	37.1	38.4	38.4
Jul	40.5	43.1	41.4	42.3	41.9	42.5	36.5	37.9	37.9
Aug	39.9	41.5	40.6	40.9	40.6	43.4	37	38.5	38.5
Sep	48.7	50.3	49.2	45.3	47.1	46	45.1	43.5	43.5
Oct	50.1	50.5	51.5	46.8	42.2	47.1	47.8	47.1	47.1
Nov	62.1	63.8	66.9	58.3	53.5	55.8	58.4	61.2	61.2
Dec	56.3	58.9	60.8	50.1	49.3	51.4	46.2	53.6	53.6



Calibrated Temperature (Living Room) **Calibrated Relative Humidity (Living Room)**

Calibrated Temperature (Bedroom 1) **Calibrated Relative Humidity (Bedroom-1)**

Calibrated Temperature (Bedroom-2) **Calibrated Relative Humidity (Bedroom-2)**

Figure 5-2 Calibrated Indoor Temperature and Relative Humidity of Case Study House 1 In Design-Builder and WUFI Plus

Table 5-8 Performance Gap of Case Study House 1

Variable	**Design-Builder**		**WUFI Plus**	
	MBE% Hourly	**Cv (RMSE)% Hourly**	**MBE% Hourly**	**Cv (RMSE)% Hourly**
Electricity	1.22	2.49	2.32	5.45
Zone Temperature (Living room)	1.87	6.71	2.1	4.97
Zone Temperature (Bedroom 1)	1.03	4.46	1.45	1.87
Zone Temperature (Bedroom 2)	1.61	7.51	1.21	2.30
Relative Humidity (Living room)	6.23	11.21	5.12	10.03
Relative Humidity (Bedroom 1)	8.11	16.301	5.36	9.45
Relative Humidity (Bedroom 2)	7.24	13.44	6.04	9.61

5.1.2.2 Calibration Results of Case Study House-2

This section presents the calibration results of Case Study House 2.

- ***Step One; Data Collection***

The input data for the Base Model of Case Study House 2 are shown in Table 5-9 below. The envelope details of the Base Model are presented in Table 5-10.

Table 5-9 Input Parameters for the Base Model of Case Study House 2

Parameter	Details
Building location	Latitude: 32.70, longitude 13.08, elevation (m) 63.0
Orientation (°)	North Axis Angle: 90
Area (²m)	85²m
WWR (%)	30%,
Glazing type	Single-glazed, internal blinds
Construction Materials	Wall: Hollow Concrete+ Cement Plaster Roof: Cast Concrete+ Asphalt+ Cement Plaster
Envelope thickness (mm)	Wall: 250 Roof: 180
Lighting Target Illuminance (lux)	100
Equipment power density (W/²m)	1.57
Occupancy template	Married_ Couple_ Two_ Children
Occupancy density (people/m^2)	0.0155
Number of occupants	6
HVAC Type	Split+ Separate Mechanical Ventilation
Operation Schedule	07:00-23:00

Table 5-10 Envelope Details of the Base Model of Case Study House 2 [6]**.**

Envelope details	Material	Thickness (mm)	λ (W/m-K)	ρ (kg/³m)	Cρ (J/Kg-K)
Wall	Cement plaster	25	1.4	600	1000
U-Value (W/m²-K) =1.557	Hollow concrete	200	0.48	880	840
	Cement plaster	25	1.4	600	1000
Roof	Asphalt	10	0.7	2100	1000
U-Value (W/m²-K) =	Cast Concrete	150	1.4	2100	840
3.139	Cement plaster	25	1.4	600	1000

- ***Step Two; Parameter Identification***

By analysing the heat balance reports of the Base Case Model of Case Study House 2 from Design-Builder and WUFI Plus, the most influencing heat gain parameters were identified and are listed in Table 5-11 below (see 3.6.1 for more details).

Table 5-11 Heat Gain Components of Case Study Houses 2

Component	Heat Gains			
	Summer		Winter	
	[W/²m]	%	[W/²m]	%
HVAC	7.1	32.3	14	42
Envelope	5.9	26.8	5.9	17.7
Window	1.3	5.9	3.5	10.5
Infiltration	6.9	31.4	1.4	4.2
Lighting	0.5	2.3	0.5	1.5
Equipment	0.3	1.36	0.3	0.9
People	0.1	0.45	0.4	0.12

For Case Study House-2, the key parameters were, in order, envelope, windows, infiltration, lighting/equipment, and people having the littlest impact on the energy demands of the HVAC system, as seen in Table 5-11.

- ***Step Three; Sensitivity Analysis***

The sensitivity analysis will be performed by changing the input values of the parameters included in Table 5-11 above, starting with the parameters that ranked highest in the table. The variables related to each parameter, which will undergo the sensitivity analysis, were listed in Table 3-19 in the methodology chapter.

Using the Influence coefficient (IC%) from equation (3.19), the sensitivity analysis results for electricity consumption and indoor temperature of Case Study House 2 are presented in Table 5-4 below.

Where: *IPBC* = Base Case input, *IPBC1* = Case 1 input, *ΔIP= IPBC-IPBC1*, *OPBC* = Base Case output, *OPBC1* = Case1 output, *ΔOP= OPBC-OPBC1*, IC= Influence Coefficient (Percentage change in the output for every 1% variation in the input).

Where: *IPBC* = Base Case input, *IPBC1* = Case 1 input, *ΔIP= IPBC-IPBC1*, *OPBC* = Base Case output, *OPBC1* = Case1 output, *ΔOP= OPBC-OPBC1*, IC= Influence Coefficient (Percentage change in the output for every 1% variation in the input).

Where:

- Base Case is the Base Case Model with the original input parameters.
- Case 1 Model is the base Case Model after varying any of the parameters under investigation.

Table 5-12 Influence Coefficient (IC%) for Electricity and Temperature of Case Study House 2

Case Study House 2								
Base Case input (Winter)		**IPBC**	**IPBC1**	**ΔIP**	**OPBC (kWh)**	**OPBC1 (kWh)**	**ΔOP (kWh)**	**IC%**
HVAC	CoP	2.25	1.85	0.4	207.5	233	-25.5	-0.691
Infiltration (ac/h)	Constant rate	1	15	-14	207.5	447	-239.5	0.082
Wall (W/m²-K)	U-value	1.557	0.5	1.057	207.5	180.9	26.6	0.189
Windows	WWR%	30%	10%	0.2	207.5	210.7	-3.2	-0.023
	U-value	5.894	1.96	3.934	207.5	201	6.5	0.047
Lighting (W/²m.100lux)	Power density	2.5	1	1.5	207.5	201.6	5.9	0.047
Equipment (W/²m)	Power density	2.16	16	-13.84	207.5	201.6	5.9	-0.004
Base Case input (Summer)		**IPBC**	**IPBC1**	**ΔIP**	**OPBC (kWh)**	**OPBC1 (kWh)**	**ΔOP (kWh)**	**IC%**
HVAC	CoP	1.8	1	0.8	161	246.5	-85.5	-1.195
Infiltration (ac/h)	Constant rate	2	15	-13	161	271.8	-110.8	0.106
Wall (W/m²-K)	U-value	1.557	0.5	1.057	161	130	31	0.284
Windows	WWR%	30%	10%	0.2	161	154.2	6.8	0.063
	U-value	5.778	1.96	3.818	161	159.1	1.9	0.018

Lighting (W/²m.100lux)		2.5	1	1.5	161	151.9	9.1	0.094
Equipment (W/²m)	Power density	2.16	16	-13.84	161	151.9	9.1	-0.009
Case Study House 2								
Base Case input (Winter)		**IPBC**	**IPBC1**	**ΔIP**	**OPBC (°C)**	**OPBC1 (°C)**	**ΔOP (°C)**	**IC%**
HVAC	Setpoint	18.00	22	-4.00	16.56	18.22	-1.66	0.451
	Setback	12	14	-2.00	16.56	16.62	-0.06	0.022
Infiltration (ac/h)	Constant rate	1	3	-2.00	16.56	16.2	0.36	-0.01
Wall (W/m²-K)	U-value	1.557	1.00	0.56	16.56	16.56	0.00	0.000
Windows	WWR%	30	10.00	20.00	16.56	16.34	0.22	0.020
	U-value	5.894	1.96	3.93	16.56	16.70	-0.14	-0.013
Lighting (W/²m.100lux)	Power density	2.5	1.00	1.50	16.56	16.54	0.02	0.002
Equipment (W/²m)	Power density	1.57	3	-1.43	16.56	16.14	0.42	-0.028
Base Case input (Summer)		**IPBC**	**IPBC1**	**ΔIP**	**OPBC (°C)**	**OPBC1 (°C)**	**ΔOP (°C)**	**IC%**
HVAC	Setpoint	25.00	22	3.00	28.19	26.36	1.83	0.541
	Setback	28	25	3.00	28.19	28.19	0.00	0.000
Infiltration (ac/h)	Constant rate	4	1	3.00	28.19	28.13	0.06	0.022
Wall (W/m²-K)	U-value	1.557	1.00	0.56	28.19	28.19	0.00	0.000
Windows	WWR%	30	10.00	20.00	28.19	28.03	0.16	0.009
	U-value	5.894	1.96	3.93	28.19	28.13	0.06	0.003
Lighting (W/²m.100lux)	Power density	2.5	1.00	1.50	28.19	28.18	0.01	0.001
Equipment (W/²m)	Power density	3	1.57	1.43	28.19	28.18	0.01	0.001

For Case Study House-2, Table 5-12 showed that the most influencing parameters in energy consumption and indoor temperature were the HVAC CoP and setpoint/setback, respectively. The calculation showed that for every ±1% variation in these parameters, there is around ±0.5% variation in the indoor temperature. The table also showed that each ±1% variation in the CoP resulted in ±0.7% and ±1.2% variation in cooling and heating loads, respectively.

Table 5-13 below are the influencing parameters ranked, in terms of IC%, from highest to lowest for Case Study House 2.

Table 5-13 Building Parameters Rankings in Terms of IC%

Energy Parameters					
Winter			**Summer**		
No.	**Parameter**	**IC% per ±1% IP**	**No.**	**Parameter**	**IC% per ±1% IP**
1	HVAC CoP	0.691	1	HVAC CoP	1.195
2	Wall U-value	0.189	2	Wall U-value	0.284
3	Infiltration	0.082	3	Infiltration	0.106
Temperature parameters					
1	HVAC Setpoint	0.45	1	HVAC Setpoint	0.541
2	Equipment	0.028	2	Infiltration	0.022
3	HVAC Setback	0.022			
4	WWR%	0.020			

Table 5-13 above shows the ranking of the most influencing parameters on energy consumption and indoor temperature for Case Study House 2. These parameters will be refined and adjusted in the next step until the building models' energy and indoor temperature are calibrated.

- ***Step Four: Adjusting Input Parameters***

After a few simulation runs (see 3.6.1 for methodology details), Case Study House 2 was calibrated.

- ***Step Five, Analysis of the Results***

Figure 5-3 below is the calibration results of the electricity consumption for Case Study House 2 in Design-Builder and WUFI Plus. Tables 5-14, 5-15 and Figure 5-4 show indoor temperature and relative humidity calibration results, respectively. The hourly performance gap, in terms of hourly MBE% and Hourly Cv (RMSE)%, For Case Study House 2 is presented in Table 5-16.

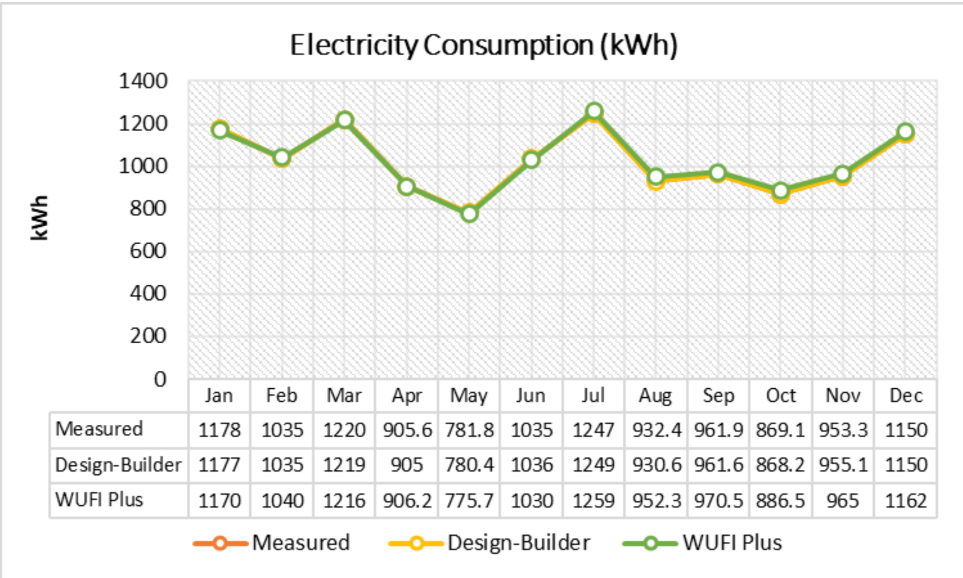


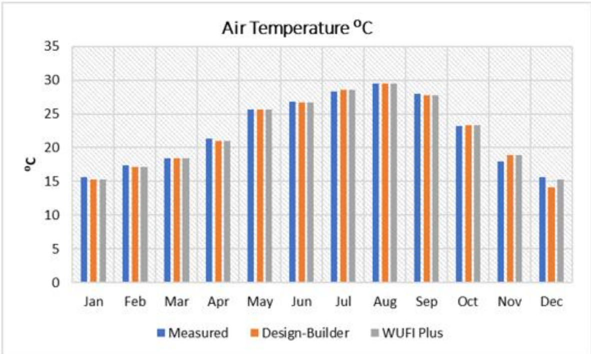
Figure 5-3 Electricity Calibration Results for Case Study House-2 in Design Builder and WUFI Plus

Table 5-14 Temperature Calibration Results for Case Study House 2 in Design-Builder and WUFI Plus

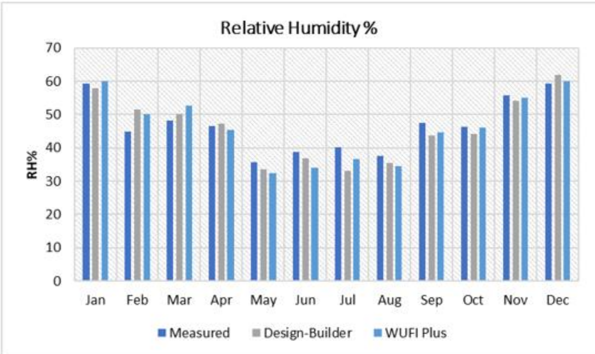
Time	Main Bedroom °C			Living room °C		
	Measured	Design-Builder	WUFI Plus	Measured	Design-Builder	WUFI Plus
Jan	15.6	15.3	15.3	15.7	15.5	16.2
Feb	17.4	17.2	17.2	16.7	16.9	17.3
Mar	18.4	18.4	18.4	18.0	17.9	18.3
Apr	21.3	21.0	21.0	21.5	21.3	21.1
May	25.7	25.7	25.7	26.8	26.5	26.9
Jun	26.8	26.7	26.7	28.2	27.9	27.9
Jul	28.3	28.5	28.5	29.4	29.3	28.9
Aug	29.5	29.5	29.5	30.5	30.4	29.9
Sep	28.0	27.7	27.7	28.9	28.8	28.5
Oct	23.2	23.3	23.3	24.3	24.4	24.9
Nov	18.0	18.9	18.9	18.0	18.9	18.6
Dec	15.6	14.1	15.3	15.7	14.1	16.2

Table 5-15 RH Calibration Results for Case Study House-2 in Design-Builder and WUFI Plus

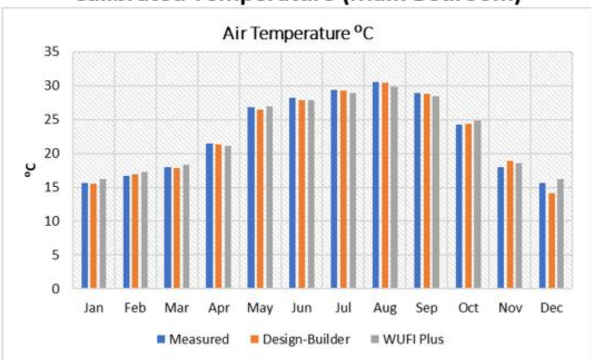
Time	Main Bedroom RH%			Living room RH%		
	Measured	Design-Builder	WUFI Plus	Measured	Design-Builder	WUFI Plus
Jan	59.4	58.0	60.1	59.5	61.8	59.5
Feb	45.0	51.4	50.1	45.4	47.1	43.9
Mar	48.2	50.2	52.6	48.2	47.2	44.7
Apr	46.6	47.3	45.4	46.3	44.7	46.9
May	35.6	33.6	32.3	35.6	36.0	35.0
Jun	38.7	36.9	34.1	38.4	38.1	39.0
Jul	40.1	33.1	36.7	39.7	41.3	40.6
Aug	37.5	35.4	34.6	37.5	36.5	37.3
Sep	47.4	43.8	44.7	47.1	47.6	46.6
Oct	46.3	44.1	46.2	46.5	43.0	48.8
Nov	55.7	54.2	55.1	55.8	57.7	55.0
Dec	59.4	62.0	60.1	59.5	57.3	59.5



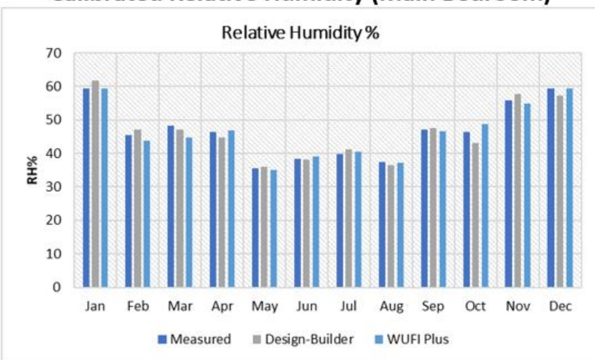
Calibrated Temperature (Main Bedroom)



Calibrated Relative Humidity (Main Bedroom)



Calibrated Temperature (Living Room)



Calibrated Relative Humidity (Living Room)

Figure 5-4 Calibrated Indoor Temperature and Relative Humidity of Case Study House 2 In Design-Builder and WUFI Plus

Table 5-16 Performance Gap for Case Study House-2

Variable	Design-Builder		WUFI Plus	
	MBE% Hourly	Cv (RMSE)% Hourly	MBE% Hourly	Cv (RMSE)% Hourly
Electricity	1.1	4.10	1.3	4.11
Air Temperature-Living room	1.14	3.67	2.24	4.97
Air Temperature-Master Bedroom	1.19	3.61	1.35	3.89
Relative Humidity-Living room	7.61	15.21	4.18	11.31
Relative Humidity-Master Bedroom	8.04	16.93	6.20	12.58

5.1.2.3 Calibration Results of Case Study House 3

This section presents the calibration results of Case Study House 3.

- ***Step One; Data Collection***

The input data for the Base Model of Case Study House 3 are shown in Table 5-17. The envelope details of the Base Model are presented in Table 5-18.

Table 5-17 Input Parameters for the Base Model of Case Study House 3

Parameter	Details
Building location	Latitude: 32.70, longitude 13.08, elevation (m) 63.0
Orientation (°)	North Axis Angle: 170
Area (²m)	140
WWR (%)	25
Glazing type	Project external glazing
Construction Materials	Wall: Limestone+ Cement Plaster Roof: Cast Concrete+ Cement Plaster
Envelope thickness (mm)	Wall: 250 Roof: 350
Lighting Target Illuminance (lux)	100
Equipment power density (W/²m)	6
Occupancy template	Married_ Couple_ Two_ Children
Occupancy density (people/m²)	0.0196
Number of occupants	6
HVAC Type	-
Operation Schedule	07:00-23:00

Table 5-18 Envelope Details of the Base Model of Case Study House 3 [6]**.**

Envelope details	Material	Thickness (mm)	λ (W/m-K)	ρ (kg/³m)	Cρ (J/Kg-K)
Wall	Cement plaster	25	1.4	600	1000
U-Value (W/m²-K) 2.683	Limestone	300	1.5	2180	720
	Cement plaster	25	2.5	1.4	600
Roof	Cast Concrete	400	1.4	2100	840
U-Value (W/m²-K) 2.236	Cement plaster	20	1.4	600	1000

- ***Step Two; Parameter Identification***

By analysing the heat balance reports of the Base Case Model of Case Study House 3 from Design-Builder and WUFI Plus, the most influencing heat gain parameters were identified and are listed in Table 5-19 below (see 3.6.1 for more details).

Table 5-19 Heat Gain Components of Case Study Houses 3

Component	Heat Gains			
	Summer		Winter	
	[W/²m]	%	[W/²m]	%
Envelope	2.9	48	1.5	32
Window	1.8	30	1.7	37
Infiltration	0.7	12	0.9	18
Lighting	0.27	5	0.27	6
Equipment	0.25	4	0.25	6
People	0.03	0.46	0.07	2

For Case Study House 3 (the free-running house), Table 5-19 showed that the key parameters are, in order, envelope, windows, infiltration, lighting/equipment, and people with the most negligible impact.

- ***Step Three; Sensitivity Analysis***

The sensitivity analysis will be performed by changing the input values of the parameters included in Table 5-19 above, starting with the parameters that ranked highest in the table. The variables related to each parameter, which will undergo the sensitivity analysis, were listed in Table 3-19 in the methodology chapter.

Using the Influence coefficient (IC%) from equation (3.19), the sensitivity analysis results for electricity consumption and indoor temperature of Case Study House 2 are presented in Table 5-20 below.

Where: *IPBC* = Base Case input, *IPBC1* = Case 1 input, *ΔIP= IPBC-IPBC1*, *OPBC* = Base Case output, *OPBC1* = Case1 output, *ΔOP= OPBC-OPBC1*, IC= Influence Coefficient (Percentage change in the output for every 1% variation in the input).

Where: *IPBC* = Base Case input, *IPBC1* = Case 1 input, *ΔIP= IPBC-IPBC1*, *OPBC* = Base Case output, *OPBC1* = Case1 output, *ΔOP= OPBC-OPBC1*, IC= Influence Coefficient (Percentage change in the output for every 1% variation in the input).

Where:

- Base Case is the Base Case Model with the original input parameters.
- Case 1 Model is the base Case Model after varying any of the parameters under investigation.

Table 5-20 Influence Coefficient (IC%) for Electricity and Temperature of Case Study House 3

Indoor temperature IC%								
Base Case input (Winter)		**IPBC**	**IPBC1**	**ΔIP**	**OPBC (kWh)**	**OPBC1 (kWh)**	**ΔOP (kWh)**	**IC%**
Infiltration (ac/h)	Constant rate	1	15	-14	79.2	79.2	0	0.000
Wall (W/m²-K)	U-value	2.683	1	1.683	79.2	39.2	40	0.805
Windows	WWR%	10%	30%	-0.2	79.2	79.2	0	0.000
	U-value	1.96	5.894	-3.934	79.2	79.2	0	0.000
Lighting (W/²m.100lux)	Power density	1	2.5	-1.5	79.2	100	-20.8	0.175
Equipment (W/²m)	Power density	10	2.16	7.84	79.2	21.4	57.8	1.000
Base Case input (Summer)		**IPBC**	**IPBC1**	**ΔIP**	**OPBC (kWh)**	**OPBC1 (kWh)**	**ΔOP (kWh)**	**IC%**
Infiltration (ac/h)	Constant rate	1	15	-14	132.8	132.4	0.4	0.000
Wall (W/m²-K)	U-value	2.683	1	1.683	132.8	65.1	67.7	0.813
Windows	WWR%	10%	30%	-0.2	132.8	132.8	0	0.000
	U-value	1.96	5.894	-3.934	132.8	132.8	0	0.000
Lighting (W/²m.100lux)		1	2.5	-1.5	132.8	201.6	-68.8	0.345
Equipment (W/²m)	Power density	10	2.16	7.84	132.8	21.4	111.4	1.149

Electricity Consumption IC%								
Base Case input (Winter)		**IPBC**	**IPBC1**	**ΔIP**	**OPBC (°C)**	**OPBC1 (°C)**	**ΔOP (°C)**	**IC%**
Infiltration (ac/h)	Constant rate	1	15	-14	10.51	11.46	-0.95	-0.14
Wall (W/m²-K)	U-value	2.68	2.00	0.68	10.51	10.59	-0.08	-0.03
Windows	WWR%	10	30	-20.0	10.51	10.51	0.00	0.000
	U-value	1.96	5.89	-3.93	10.51	10.46	0.05	-0.002
Lighting (W/²m.100lux)	Power density	2.5	1.00	1.50	10.51	10.5	0.01	0.002
Equipment (W/²m)	Power density	2.16	10	-7.84	10.51	10.57	-0.06	0.002
Base Case input (Summer)		**IPBC**	**IPBC1**	**ΔIP**	**OPBC (°C)**	**OPBC1 (°C)**	**ΔOP (°C)**	**IC%**
Infiltration (ac/h)	Constant rate	1	15	-14	32.33	31.41	0.92	0.043
Wall (W/m²-K)	U-value	2.683	2.00	0.68	32.01	28.19	3.82	0.469
Windows	WWR%	10	30	-20.0	32.33	32.33	0.00	0.000
	U-value	1.96	5.89	-3.93	32.33	32.33	0.00	0.000
Lighting (W/²m.100lux)		2.5	1.00	1.50	32.33	32.3	0.03	0.002
Equipment (W/²m)	Power density	10	2.16	7.84	32.33	31.26	1.07	0.042

The table above shows that for Case Study House 3 (free running), the most influencing parameter in terms of electricity consumption was the equipment, as ±1% variation in this parameter resulted in around ±1% and ±1.2% variation in the energy consumption in both summer and winter, respectively. For the indoor temperature, Table 5-20 showed that the highest influencing parameters were infiltration in Winter and Wall's U-value in Summer, as the calculation showed that every ±1% variation in these parameters would result in around ±0.1 % and 0.5% variation in the indoor temperature in both winter and summer, respectively.

Table 5-21 below are the influencing parameters ranked, in terms of IC%, from highest to lowest for Case Study House 3.

Table 5-21 Building Parameters Rankings in Terms of IC%

Case Study-3 (Energy Parameters)					
Winter			**Summer**		
No.	**Parameter**	**IC% per ±1% IP**	**No.**	**Parameter**	**IC% per ±1% IP**
1	Equipment	1	1	Equipment	1.149
2	Wall U-value	0.805	2	Wall U-value	0.813
3	Lighting	0.175	3	Lighting	0.345
Case Study-3 (Temperature parameters)					
1	Infiltration	0.136	1	Wall U-value	0.469
2	Wall U-value	0.030	2	Infiltration	0.43
3	Equipment	0.002	3	Equipment	0.042

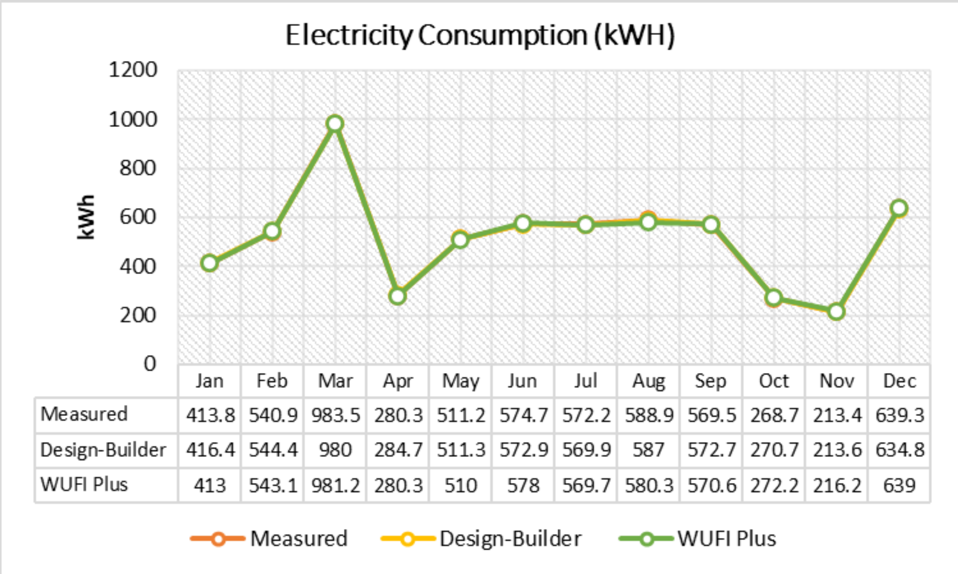
Table 5-21 above shows the ranking of the most influencing parameters on energy consumption and indoor temperature for Case Study House 3. These parameters will be refined and adjusted in the next step until the building models' energy and indoor temperature are calibrated.

- ***Step Four: Adjusting Input Parameters***

After a few simulation runs (see 3.6.1 for methodology details), Case Study House 3 was calibrated.

- ***Step Five, Analysis of the Result***

Figure 5-5 presents the calibrated energy consumption for Case Study House 3 in Design-Builder and WUFI Plus. Tables 5-22, 5-23, and Figures 5-6 present the calibrated indoor temperature and relative humidity of Case Study House 3. The hourly performance gap, in terms of hourly MBE% and Hourly Cv (RMSE)%, For Case Study House 3 is presented in Table 5-24.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Measured	413.8	540.9	983.5	280.3	511.2	574.7	572.2	588.9	569.5	268.7	213.4	639.3
Design-Builder	416.4	544.4	980	284.7	511.3	572.9	569.9	587	572.7	270.7	213.6	634.8
WUFI Plus	413	543.1	981.2	280.3	510	578	569.7	580.3	570.6	272.2	216.2	639

Figure 5-5 Electricity Calibration Results for Case Study House 3 in Design Builder and WUFI Plus

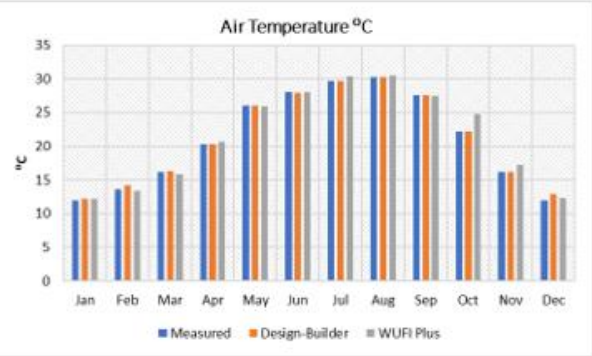
Table 5-22 Temperature Calibration Results-Case Study House 3 in Design-Builder and WUFI Plus

Time	Living Room °C			Bedroom 3 °C			Lounge °C		
	Measured	Design Builder	WUFI Plus	Measured	Design Builder	WUFI Plus	Measured	Design Builder	WUFI Plus
Jan	12.0	12.2	12.2	12.1	12.4	12.8	11.7	12.2	12.1
Feb	13.6	14.2	13.4	13.6	14.4	14.1	12.6	14.1	13.0
Mar	16.2	16.3	15.8	16.4	16.6	16.0	15.2	16.2	15.4
Apr	20.3	20.3	20.7	20.1	20.0	19.6	19.8	19.7	19.5
May	26.0	26.0	25.9	26.3	26.5	26.1	25.9	26.2	25.6
Jun	28.0	27.9	28.0	28.4	28.4	27.6	28.1	26.4	27.8
Jul	29.7	29.7	30.4	29.4	29.4	29.5	29.4	28.5	29.2
Aug	30.3	30.3	30.5	31.0	30.8	30.7	30.2	30.2	30.0
Sep	27.6	27.6	27.5	28.2	28.2	27.9	27.6	26.5	27.2
Oct	22.2	22.2	24.8	22.6	22.7	24.7	22.2	21.6	24.4
Nov	16.2	16.2	17.3	16.0	16.5	17.3	15.3	16.2	17.1
Dec	12.0	12.9	12.3	12.3	13.1	12.4	12.7	12.9	12.3

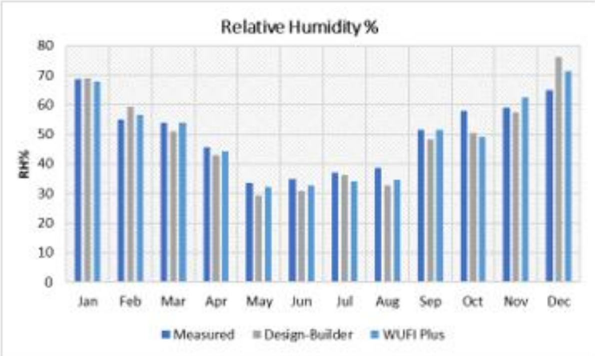
Table 5-23 RH% Calibration Results-Case Study House 3 in Design-Builder and WUFI Plus

Time	Living Room RH%			Bedroom 3 RH%			Lounge RH%		
	Measured	Design Builder	WUFI Plus	Measured	Design Builder	WUFI Plus	Measured	Design Builder	WUFI Plus
Jan	68.6	68.8	67.8	68.9	63.0	65.3	69.3	65.7	67.5
Feb	55.0	59.4	56.6	56.0	54.7	56.5	57.0	58.3	56.7
Mar	54.0	50.9	53.8	55.2	51.3	53.5	56.4	53.5	55.2
Apr	45.7	42.8	44.2	46.8	48.9	46.0	47.9	46.0	49.1
May	33.5	29.2	32.2	34.2	29.7	32.3	34.9	32.9	35.7
Jun	35.0	30.8	32.8	35.9	36.1	34.0	36.9	34.1	38.5

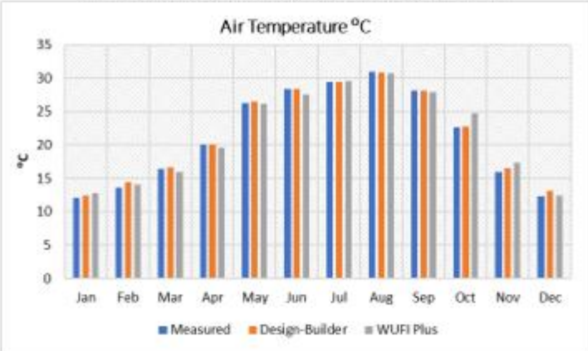
Jul	37.1	36.1	34.2	38.6	34.7	36.6	40.0	38.1	37.3
Aug	38.7	32.7	34.6	39.2	37.0	35.2	39.7	35.9	39.6
Sep	51.4	48.2	51.5	51.7	55.1	49.9	52.0	51.3	56.8
Oct	58.0	50.4	49.0	46.3	47.4	44.6	48.2	45.6	42.1
Nov	59.0	57.3	62.6	57.5	59.1	60.8	59.6	62.0	55.8
Dec	65.0	76.1	71.2	65.5	72.1	70.8	65.0	71.6	69.1



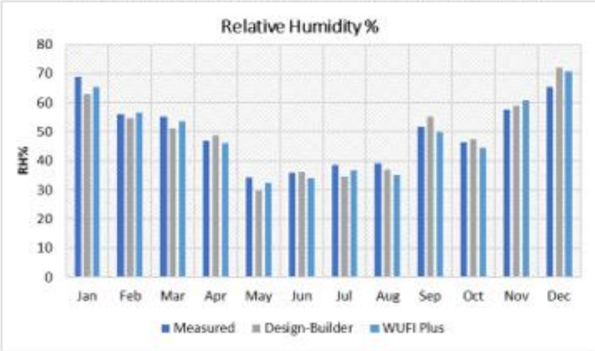
Calibrated Temperature (Living Room)



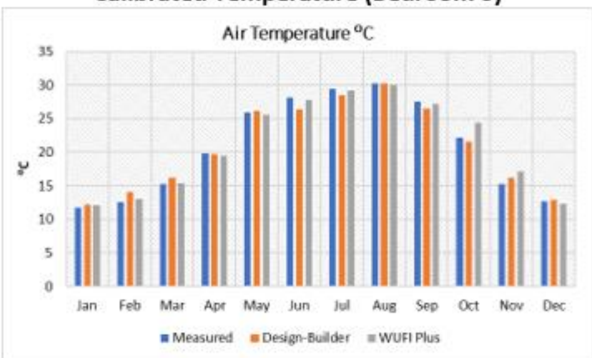
Calibrated Relative Humidity (Living Room)



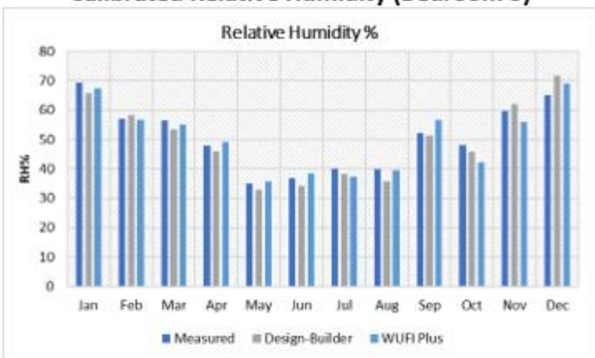
Calibrated Temperature (Bedroom 3)



Calibrated Relative Humidity (Bedroom 3)



Calibrated Temperature (Lounge)



Calibrated Relative Humidity (Lounge)

Figure 5-6 Calibrated Indoor Temperature and Relative Humidity of Case Study House 3 In Design-Builder and WUFI Plus

Table 5-24 Performance Gap for Case Study House-2

Variable	Design-Builder		WUFIPlus	
	MBE% Hourly	Cv (RMSE)% Hourly	MBE% Hourly	Cv (RMSE)% Hourly
Electricity	2.48	4.55	1.33	3.62
Zone Temperature (Living room)	1.89	8.53	1.91	2.32
Zone Temperature (Bedroom 3)	1.23	4.74	1.56	1.99
Zone Temperature (Lounge)	3.49	4.39	2.09	4.46

Relative Humidity (Living room)	9.22	20.19	5.98	9.09
Relative Humidity (Bedroom 3)	8.86	19.26	4.74	9.91
Relative Humidity (Lounge)	9.11	19.32	3.04	9.36

This section presented the calibration results of the three Case Study Houses, using the methodology adopted from published research and presented in chapter 3, section 3.6.1. The results confirm that the selected calibration variables (electricity consumption, indoor temperature, and relative humidity) are now calibrated for the three Case Studies. Tables 5-8, 5-16, and 5-24 showed the performance gap between the measured and simulated variables for the three Case Studies' in terms of hourly MBV% and hourly Cv (RMSE). The hourly MBV% and Cv (RMSE) results confirm that the three Case Study models are now calibrated to the satisfactory accuracy criteria set by the three international organizations ASHRAE, EVO and FEMP (see 2.3.2. and 3.6.1).

As mentioned before, two of the Case Studies are mechanically equipped for heating and cooling. The third Case Study was a free running house with no active heating or cooling. This was challenging at first, as it was not possible to use the influence of some parameters, such as the heating and cooling setpoints and setbacks to calibrate the temperature or to use the HVAC CoP to calibrated the energy consumption. The calibration process is simply the tunning of variable parameters in order to reduce the performance gap and to match the measured and simulated data. It was possible after all to calibrated the Case Study House 3 with a minimum performance gap after few simulation runs and by changing some of the other parameters that have an impact on the indoor thermal conditions and the energy consumption (see Table 5-20).

5.2 Building Performance Simulation in Design-Builder and WUFI Plus

5.2.1 Methodology

The calibrated models from Design-Builder and WUFI Plus (see 5.1) will be used to assess the impact of changing the wall materials on the hygrothermal performance of the Case Study Houses. The detailed simulation methodology is described in section 3.6.

The heat balance reports from Design-Builder are presented in the next section for the three Case Studies. These will help define heat gain and loss components in the Case Study Buildings and provide a better understanding of the impact of envelope materials and design on the hygrothermal performance of the Case Study Houses.

5.2.2 Heat Balance of the Case Study Houses

Below are the heat balance reports from Design-Builder for the three Case Study Houses.

- ***Case Study House 1***

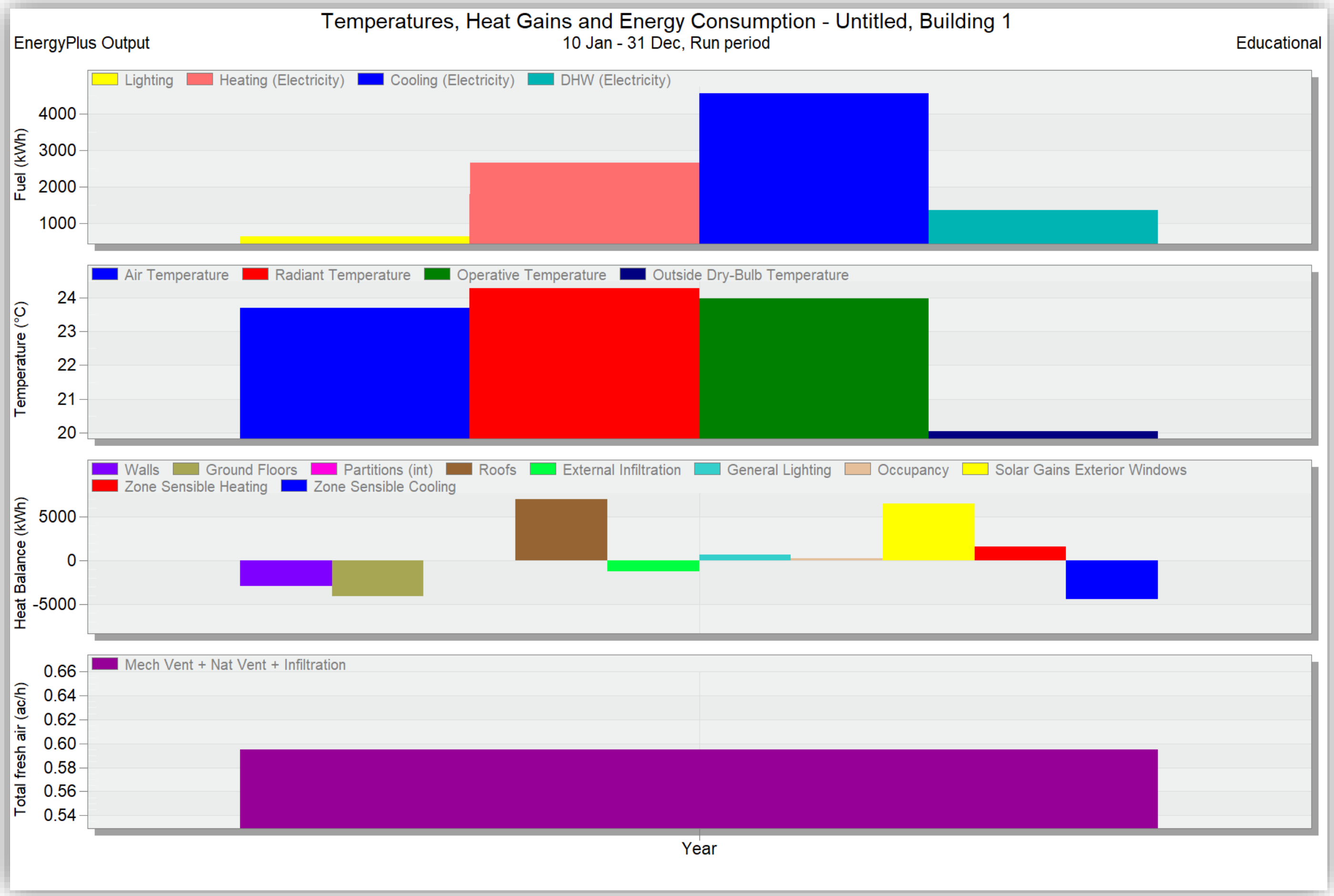


Figure 5-7 Heat Balance Report for Case Study House 1

Figure 5-7 above shows the heat balance report of Case Study House 1. The figure shows the highest heat gains for the Case Study are through the roof and windows. The figure also showed heat losses through the floor and walls of the Case Study House.

- **Case Study House 2**

Figure 5-8 below shows the heat balance report for Case Study House 2 in Design-Builder. The figure shows that the main heat gain components in Case Study House 2 are the roof and windows. There is also heat loss through the wall and floor of Case Study House 2, as seen from the figure.

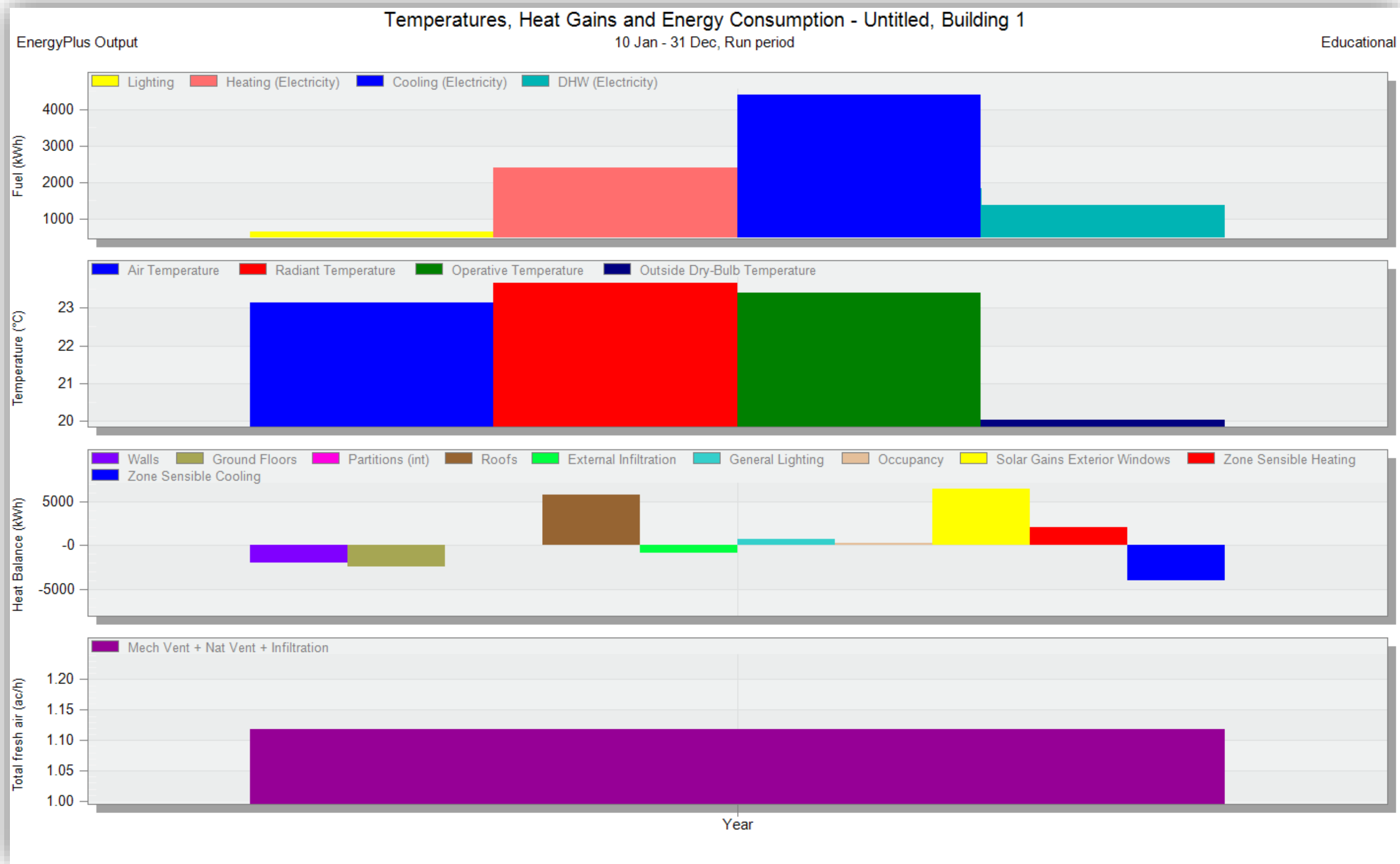


Figure 5-8 Heat Balance Report for Case Study House 2

- **Case Study House 3**

The heat balance report for Case Study House 3 from Design-Builder is shown in Figure 5-9 below.

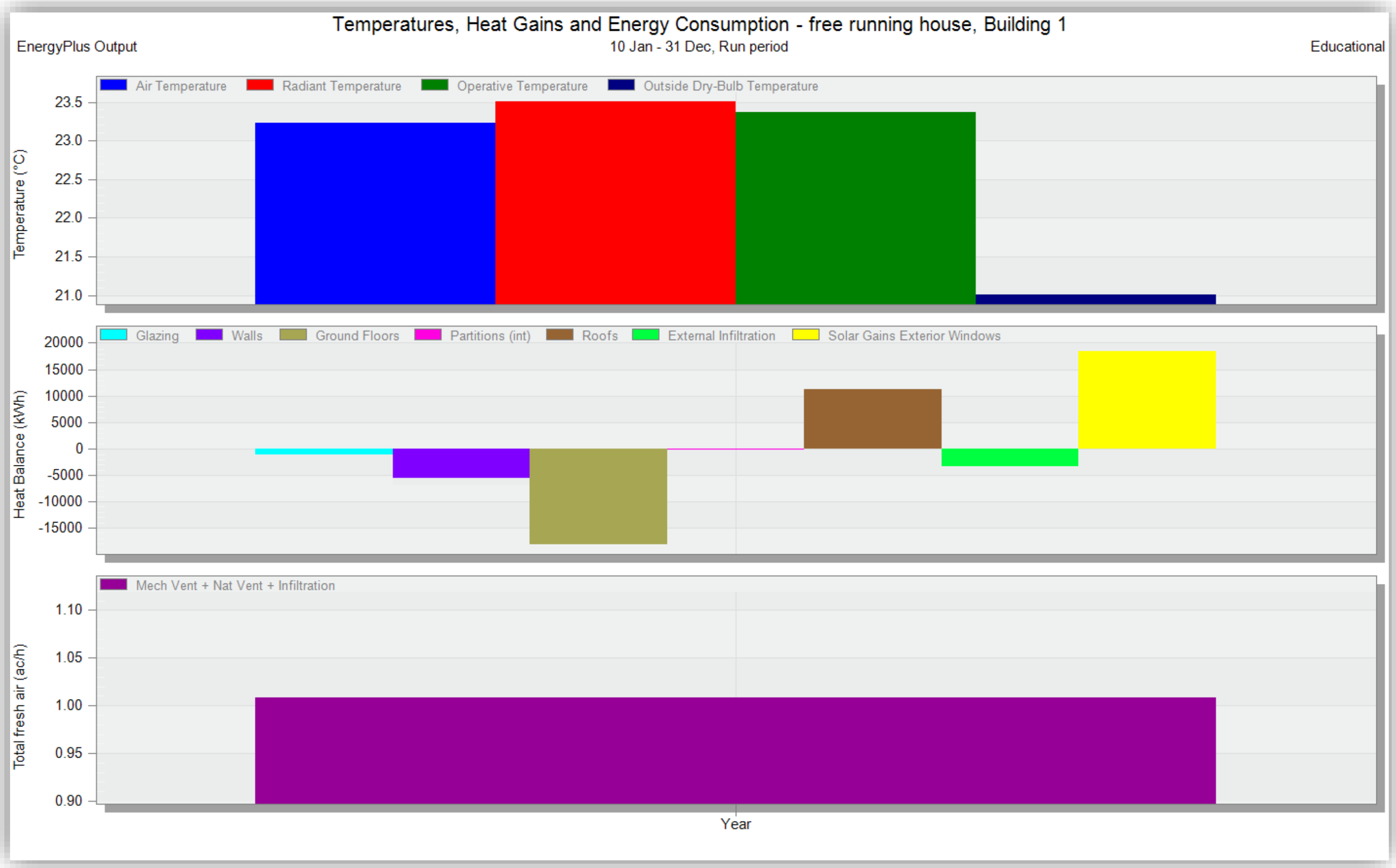


Figure 5-9 Heat Balance Report for Case Study House 3

Similar to the other two Case Studies, Figure 5-9 showed that the heat gain is mainly through windows and roof, with heat loss also through the floor and walls of Case Study House 3.

As mentioned before, this thesis focuses on the hygrothermal properties of some common building materials from Libya and how can be integrated into efficient wall assemblies that could improve hygrothermal comfort in domestic buildings in Libya. Observation from analysing the three Case Studies' heat balance reports is that the main components affecting the heat gain and losses in the Case Study Houses are the roofs, windows, floors, and walls. To better evaluate the hygrothermal performance of the suggested walls, Heat gains and losses through roofs, windows and floors must be minimized. Therefore, a sensitivity analysis will be performed using a Test Cell Model with an optimized roof, windows and floor, as was described in 3.5.6.

5.2.3 Sensitivity Analysis Results for Building Materials and Wall Design Choice

(See 3.5.6. for the sensitivity analysis methodology details). The sensitivity analysis presented in this section was conducted using WUFI Plus software due to its demonstrated flexibility and capability in simulating indoor hygrothermal conditions, as compared to the Design-Builder software [168]. The sensitivity analysis was performed to reduce the number of simulations by focusing on material and wall configurations that have the highest impact on the hygrothermal conditions of the Test Cell Model. Hence, through analysing the following:

- **a)** Impact of changing wall materials on the hygrothermal conditions of the Test Cell Model.
- **b)** Impact of wall design choice on the hygrothermal conditions of the Test Cell Model.
- **c)** Impact of Insulation Layer Position on the hygrothermal conditions of the Test Cell Model.

Table 5-25 below shows the indoor hygrothermal conditions of the Test Cell Model.

Table 5-25 Indoor Hygrothermal Condition of the Test Cell Model

Time	Out-RH%	In-RH%	Out-Temp °C	In-Air-Temp °C	In-Rad-Temp °C	In-Oper-Temp °C
Jan	65.8	42.6	11.4	16.0	16.6	16.3
Feb	62.8	43.5	13.4	17.2	17.7	17.4
Mar	60.8	42.2	15.2	18.8	19.2	19.0
Apr	51.4	45.5	20.7	20.2	20.3	20.2
May	37.4	42.0	26.7	23.4	23.0	23.2
Jun	39.9	50.1	28.1	23.9	23.6	23.7
Jul	43.9	57.8	29.4	24.8	24.3	24.5
Aug	43.1	58.8	31.8	25.5	24.9	25.2
Sep	51.9	51.3	28.5	24.0	23.6	23.8
Oct	65.2	67.4	20.7	20.8	20.8	20.8
Nov	75.9	50.1	14.2	18.2	18.6	18.4
Dec	68.5	48.4	9.9	16.6	17.2	16.9

5.2.3.1 Impact of Changing Wall Materials on the Hygrothermal Conditions of the Test Cell Model

The walls of the Test Cell Model are made of Limestone (250mm) with 25mm Cement Plaster on both sides. The first set of simulations uses the following materials (single-layer wall with only one material);

- **W1LS** (Limestone 200mm),

- **W1HC** (Hollow Concrete 200mm),
- **W1SS** (sandstone 200mm),
- **W1MB** (Mud Block 200mm),
- **W1CL** (Clay 200mm),
- **W1CH** (Camel's Hair 200mm).

For sensitivity analysis (as mentioned in the methodology chapter), Case Study House 3 will be used as Test Cell Model to analyse the impact of material and wall design choice on the hygrothermal conditions. Details of the Test Cell Model and its improved roof, floors and windows of the Test Cell Model were presented in 3.6.5.

The simulation results helped identify which wall materials had the highest impact on the indoor hygrothermal conditions of the Test Cell Model. Figure 5-10 below showed that W1CH (Camel's Hair 200), followed by W1LS (Limestone 200mm) and W1MB (Mud Block 200m), had the highest impact on the indoor Hygrothermal conditions of the Test Cell Model.

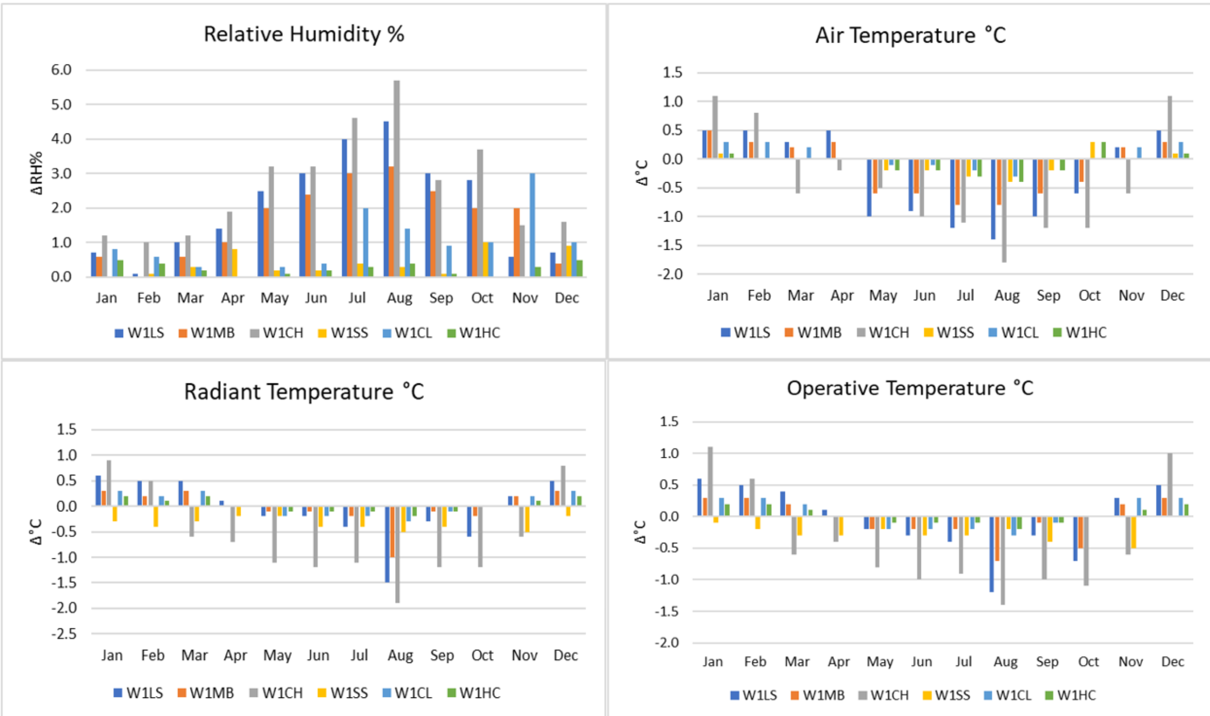


Figure 5-10 Impact of Replacing Original Wall Material with the Selected Materials on Indoor Hygrothermal Conditions of the Test Cell Model

The Figure above shows the impact of material change on the hygrothermal conditions of the Test Cell Model (TCM). The simulation showed a minimum impact of Hollow Concrete (W1HC) and Sandstone (W1SS) on the hygrothermal conditions of the TCM. The Figure showed an increase in RH% levels for the remaining materials between 1% during summer and 6% during winter. The highest increase in RH% level is in August, with 5.8% for Camel's hair (W1CH), 4.3% for Limestone (W1LS) and 3% for Mud Block (W1MB).

In terms of indoor air temperature, the Figure showed that W1CH (Camel's hair), followed by W1LS (Limestone) and W1MB (Mud Block), had the highest impact on the indoor temperature.

The Figure showed a positive impact of these materials on the indoor air temperature during both the summer and winter months. in August, the Figure showed that the air temperature was reduced by 1.7°C when using Camel's hair (W1CH), 1.4 °C when using (Limestone) and by 0.8°C when using W1MB (Mud Block). During the coldest months (December and January), the air temperature increased by 1°C when using Camel's hair (W1CH) and by 0.5 °C when using Limestone (W1LS) and Mud Block (W1BM).

In the following subsection, wall configurations (See Table 3-28 and Figures 3-24 to 3-28) with the highest impact on the hygrothermal conditions of the Test Cell Model will be identified. As Camel's hair, Limestone and Mud Block had the highest impact on the hygrothermal conditions, these materials will be used for the simulation in the following subsection.

5.2.3.2 Impact of Wall Design Choice on the Hygrothermal Conditions of the Test Cell Model.

After identifying which wall material had the highest impact, further simulations were performed to determine which wall configurations would have the highest impact on the indoor hygrothermal conditions of the Test Cell Model.

The walls of the Test Cell Model are made of Limestone (250mm) with 25mm Cement Plaster on both sides. The first set of simulations uses the following wall configurations;

- **W-1** (Material 200mm),
- **W-2** (Material 300mm),
- **W-3** (Cement Plaster 25mm+ Material 200mm+ Cement Plaster 25mm),
- **W-4** (Cement Plaster 25mm+ Material 300mm+ Cement Plaster 25mm),
- **W-5** (Clay Plaster 25mm+ Material 200mm+ Clay Plaster 25mm),
- **W-6** (Clay Plaster 25mm+ Material 300mm+ Clay Plaster 25mm),
- **W-7**(Cement Plaster 25mm+ Material 100mm+ Camels Hair insulation 100mm+ Material 100mm+ Cement Plaster 25mm),
- **W-8** (Clay Plaster 25mm+ Material 100mm+ Camels Hair insulation 100mm+ Material 100mm+ Clay Plaster 25mm),

The results are presented in the Figure below.

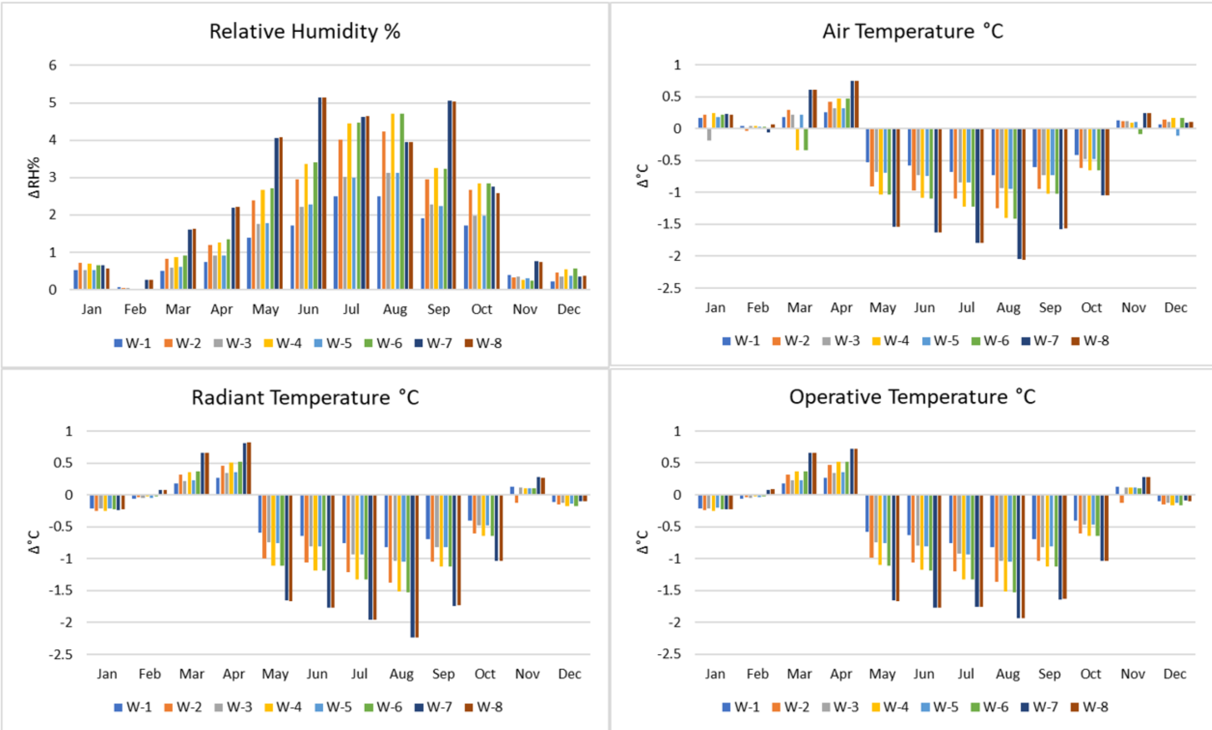


Figure 5-11 Impact of Replacing Existed Wall Design With the Suggested Wall Designs on the Indoor Hygrothermal Conditions of The Test Cell Model

It can be seen from the Figure that walls W8 (Material+ Camel's hair insulation+ Clay Plaster) and W7 (Material+ Camel's hair insulation+ Cement Plaster) had the highest impact on the hygrothermal conditions of the Test Cell Model.

The Figure showed that the two wall configurations could reduce the indoor temperature in the range of 1.5°C -2.1°C between May and October. During March and April, the indoor temperature increases by around 0.7°C with wall W8 (Material+ Camel's hair insulation+ Clay Plaster) and W7 (Material+ Camel's hair insulation+ Cement Plaster). There was not much impact for any of the walls on the indoor temperature during cold months (November-February), as seen in the Figure.

The Figure also showed that the two walls, W8 (Material+ Camel's hair insulation+ Clay Plaster) and W7 (Material+ Camel's hair insulation+ Cement Plaster), helped increase the indoor RH during dry summer months with around 4% in May, 5% in June, 4.4% in July, 4% in August and 5% in September.

5.2.3.3 Impact of Insulation Layer Position on the Hygrothermal Conditions of the Test Cell Model

Before conducting the hygrothermal performance simulations, it was necessary to investigate the impact of changing the insulation layer position within the wall on the hygrothermal conditions of the Test Cell Model. For this reason, the following two configurations were compared;

a) ***(Wall-A)*** Insulation between two layers of material and plaster on both sides of the wall (Figure 5-12). Wal-A consists of the following materials (from outside to inside);

- *Clay plaster 25mm*
- *Limestone 100mm*
- *Camel's hair 100mm*
- *Limestone 100mm*
- *Clay plaster 25mm*

b) ***(Wall-B)*** Insulation on the inside surface of the wall with plaster on both sides (Figure 5-13). This wall comprises the following materials (from outside to inside);

- *Clay plaster 25mm*
- *Limestone 200mm*
- *Camel's hair 100mm*
- *Clay plaster 25mm*

The results of changing the insulation layer position are presented in Figure 5-14 below.

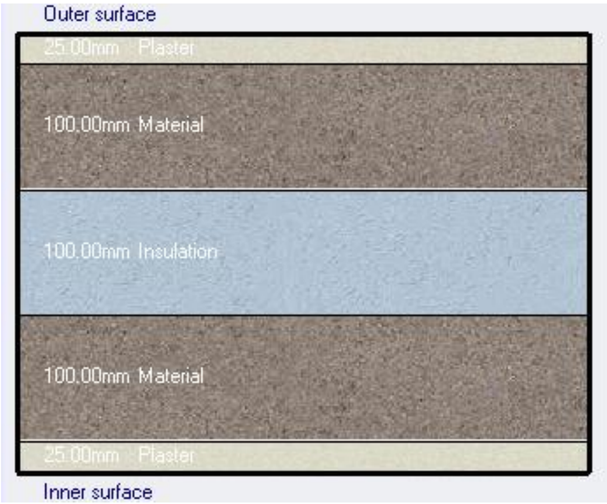


Figure 5-12 Wall-A, Insulation Between Two Layers of Material

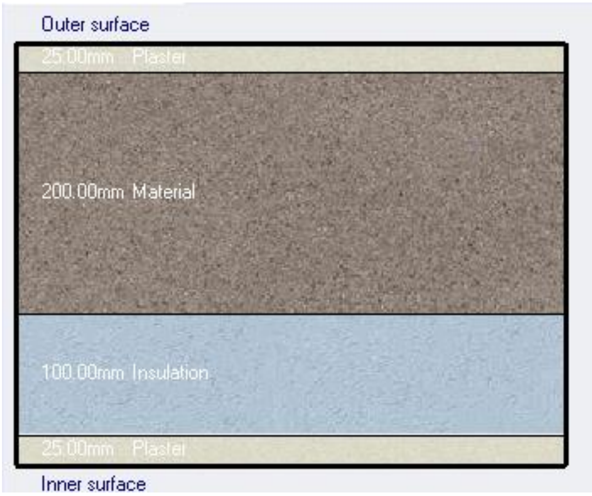


Figure 5-13 Wall-B, Insulation on the inside of the Wall

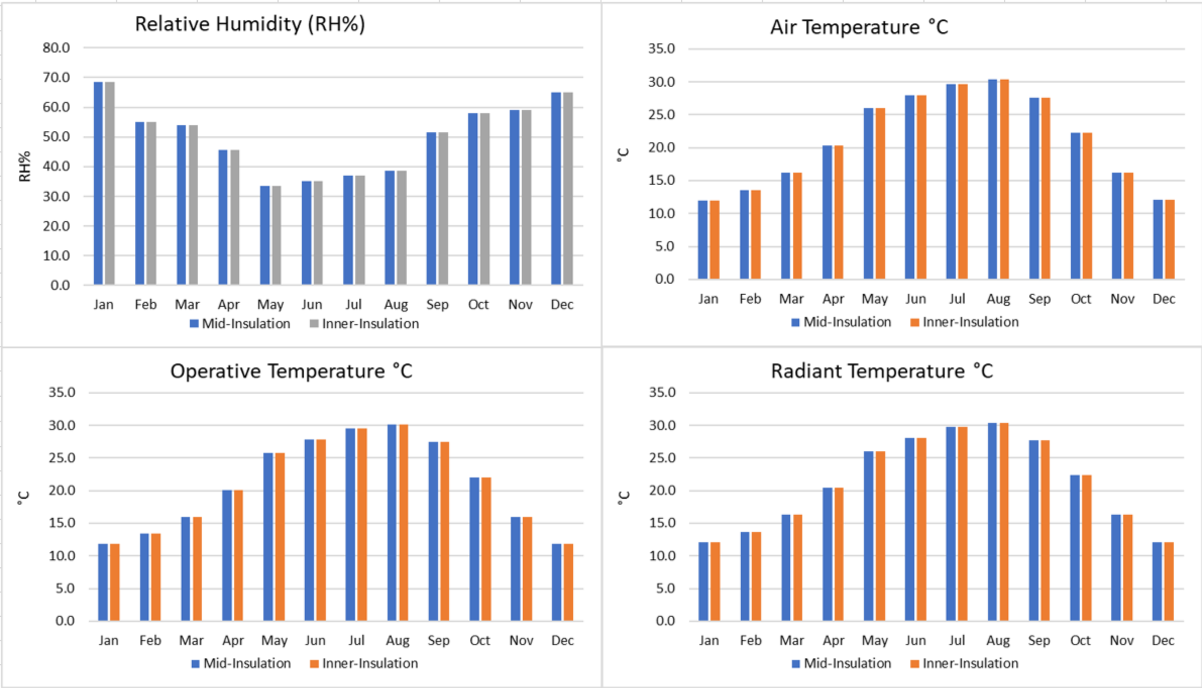


Figure 5-14 Impact of Changing the Insulation Layer Position on the Hygrothermal Conditions of the Test Cell Model

Figure 5-14 showed that the insulation layer position had no impact on the hygrothermal conditions of the Test Cell Model. This might be because the internal Clay Plaster layer on the wall affects its hygrothermal performance.

From the above and the sensitivity analysis results, the best promising walls in terms of providing hygrothermal comfort are the following:

- **Wall W2CH** (Clay Plaster 25mm + Camel's hair 300mm + Clay Plaster 25mm).
- **Wall W8LS** (Clay Plaster 25mm + Limestone 100mm + Camel's hair insulation 100mm + Limestone 100mm + Clay Plaster 25mm).
- **Wall W8MB** (Clay Plaster 25mm + Mud Block 100mm + Camel's hair insulation 100mm + Mud Block 100mm + Clay Plaster 25mm).

5.2.4 Hygrothermal Behaviour Modelling

The section presents the results of the hygrothermal behaviour assessment in WUFI 2D. The walls that had the highest impact on the hygrothermal conditions from the sensitivity analysis will be the subject of simulations in this section.

The hygrothermal behaviour of the selected walls will be evaluated using WUFI 2D 4.1 under representative climate conditions. Thus, the objective of the simulations is to detect risks of condensation, problems of dryness, and mould growth in walls W2CH (Camel's hair + Clay Plaster

350mm), Wall W8LS (Limestone +Camel’s hair insulation+ Clay Plaster 350mm), and Wall W8MB (Mud Block+ Camel’s hair insulation+ Clay Plaster 350mm) under the Libyan climate.

5.2.4.1 Methodology

The hygrothermal behaviour evaluation of the selected walls is based on the assessment of the following criteria;

- Total Moisture Content (TMC).
- Dryness Rate (DR).
- Condensation Risk (CR).
- Mould Growth
- ASHRAE-160 Criteria.

The detailed hygrothermal behaviour simulation methodology was presented in section 3.6.6.

5.2.4.2 Results and Discussion

This section presents the hygrothermal behaviour simulation results of Wall W2CH (Camel’s hair + Clay Plaster 350mm), Wall W8LS (Limestone +Camel’s hair insulation+ Clay Plaster 350mm), and Wall W8MB (Mud Block+ Camel’s hair insulation+ Clay Plaster 350mm). The results are analysed based on the output from WUFI 2D and the hygrothermal evaluation criteria.

- ***Total Moisture Content (TMC);***

Excessive moisture in building materials can lead to materials deterioration, mould growth and possible structural damage to the building. Total Moisture Content criteria indicate the wall's ability to dry with time. To pass this criterion, the wall’s final moisture content must be lower than its initial moisture content.

Figure 5-15 show the Total Moisture Content for Walls W2CH (Camel’s hair + Clay Plaster 350mm), Wall W8LS (Limestone +Camel’s hair insulation+ Clay Plaster 350mm), and Wall W8MB (Mud Block+ Camel’s hair insulation+ Clay Plaster 350mm).

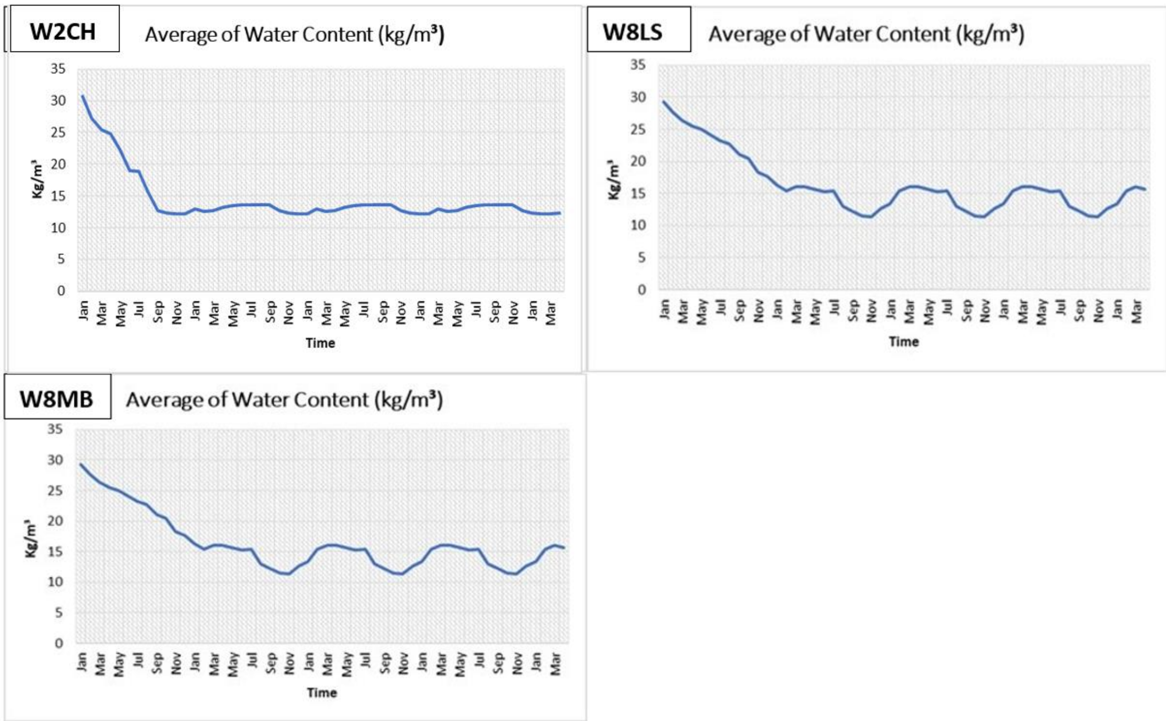


Figure 5-15 Average Total Moisture Content (TMC%)

W2CH (Camel's hair + Clay Plaster 350mm), W8LS (Limestone +Camel's hair insulation+ Clay Plaster 350mm), and W8MB (Mud Block+ Camel's hair insulation+ Clay Plaster 350mm)

The Figures showed that all walls were able to release the accumulated moisture over time. In approximately the first 360 days, the initial moisture in wall W8LS (Limestone +Camel's hair insulation+ Clay Plaster 350mm) drops from around 28% to 15%. In wall W8MB (Mud Block+ Camel's hair insulation+ Clay Plaster 350mm), the initial MC dropped from about 30% to nearly 17% in the first 360 days. For wall W2CH (Camel's hair + Clay Plaster 350mm), the initial moisture content reaches equilibrium in approximately 270 days, as the MC drops from 20% to around 13%.

The Figures also showed that in wall W2CH (Camel's hair + Clay Plaster 350mm), the moisture uptake/release curve is almost flat and ranges between 13% during winter and 11% during summer. For the other two walls (W8LS and W8MB), the Figure showed that both walls were able to release the moisture they absorbed during winter. Although it took longer for W8MB (Mud Block+ Camel's hair insulation+ Clay Plaster 350mm) to reach equilibrium MC compared to W8LS (Limestone +Camel's hair insulation+ Clay Plaster 350mm).

The simulation results showed that wall W8MB (Mud Block+ Camel's hair insulation+ Clay Plaster 350mm) had higher moisture sorption/desorption capacity than the other two walls. In Figure 5-15, the lowest and highest moisture content after four winter cycles for wall W8LS (Limestone +Camel's hair insulation+ Clay Plaster 350mm) are 15% and 11%, respectively. For wall W8MB (Mud Block+ Camel's hair insulation+ Clay Plaster 350mm), Figure 5-15 showed that the highest and lowest moisture content after the four winter cycles are 22% and 11%, respectively, and for wall W2CH

(Camel's hair + Clay Plaster 350mm), the highest and lowest moisture content after the four winter cycles are 14% and 11%, respectively.

The results of the Total Moisture Content criteria show that all walls can dry out over time; hence, all walls have passed this criterion.

- ***Dryness Rate (DR);***

The dryness rate is the difference between the initial and the final moisture content. The higher the DR, the greater the ability of the wall to dry out. If the DR values are negative, the wall absorbs moisture and humidity; if the values are positive, the wall rejects moisture and humidity. The DR of wall W2CH (Camel's hair + Clay Plaster 350mm), wall W8LS (Limestone +Camel's hair insulation+ Clay Plaster 350mm), and wall W8MB (Mud Block+ Camel's hair insulation+ Clay Plaster 350mm) is presented in the Figure below.

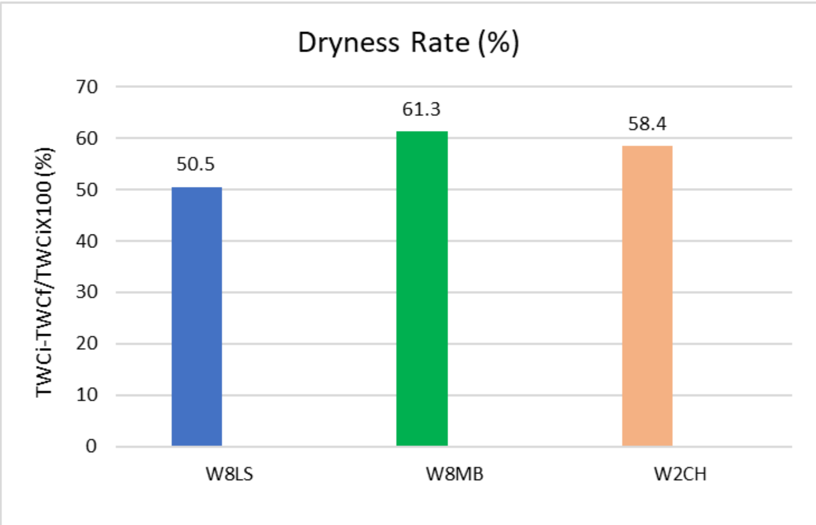


Figure 5-16 Dryness Rate (%)

W2CH (Camel's hair + Clay Plaster 350mm), W8LS (Limestone +Camel's hair insulation+ Clay Plaster 350mm), and W8MB (Mud Block+ Camel's hair insulation+ Clay Plaster 350mm)

The simulation results confirm that all walls have passed the DR criteria. The Figure shows that all walls have a positive DR rate (with minimum 50.5% DR for W8LS). The figure also showed that the highest DR Rate is for wall W8MB (Mud Block+ Camel's hair insulation+ Clay Plaster 350mm) with 61.3%, followed by W2CH (Camel's hair + Clay Plaster 350mm) at 58.4% and W8LS (Limestone +Camel's hair insulation+ Clay Plaster 350mm) with 50.5% dryness rate.

While there are no universally accepted benchmarks for dryness rate of building materials, references such as guidelines and standards published by ASTM, and building codes and regulations, can provide useful benchmarks for evaluating the performance of building materials in terms of moisture control and dryness rate [169]–[171].

- ***Condensation Risk (CR)***:

Condensation can occur if the surface temperature falls below the air dew temperature. The risk of condensation increases with the increased duration of temperature difference. Condensation Risk can be explained by the direct contact between the walls and the cold outdoor temperature, which leads to low indoor surface temperature, or by the high RH level in the wall. Since the temperature in all walls remains above 14°C and RH below 70% (Figures 5-18, 5-19 and 5-20), the risk of condensation was calculated, and the results showed a 0% CR for all walls. The Condensation Risk results confirm that walls W2CH (Camel's hair + Clay Plaster 350mm), Wall W8LS (Limestone +Camel's hair insulation+ Clay Plaster 350mm), and Wall W8MB (Mud Block+ Camel's hair insulation+ Clay Plaster 350mm) pass the CR criteria.

- ***Mould Growth:***

Mould is dependent on the surface RH and temperature as well as the duration of the RH condition "(80% RH on a mean monthly basis)" (Kuka et al., 2022). Figure 5-17 below shows the isopleth generated from WUFI 2D. They showed that the hygrothermal condition in all walls remains under the LIMI and LIMII curves, which means that mould growth is unlikely for walls W2CH (Camel's hair + Clay Plaster 350mm), Wall W8LS (Limestone +Camel's hair insulation+ Clay Plaster 350mm), and Wall W8MB (Mud Block+ Camel's hair insulation+ Clay Plaster 350mm) under the Libyan climate. Hence, all walls have passed this criterion.

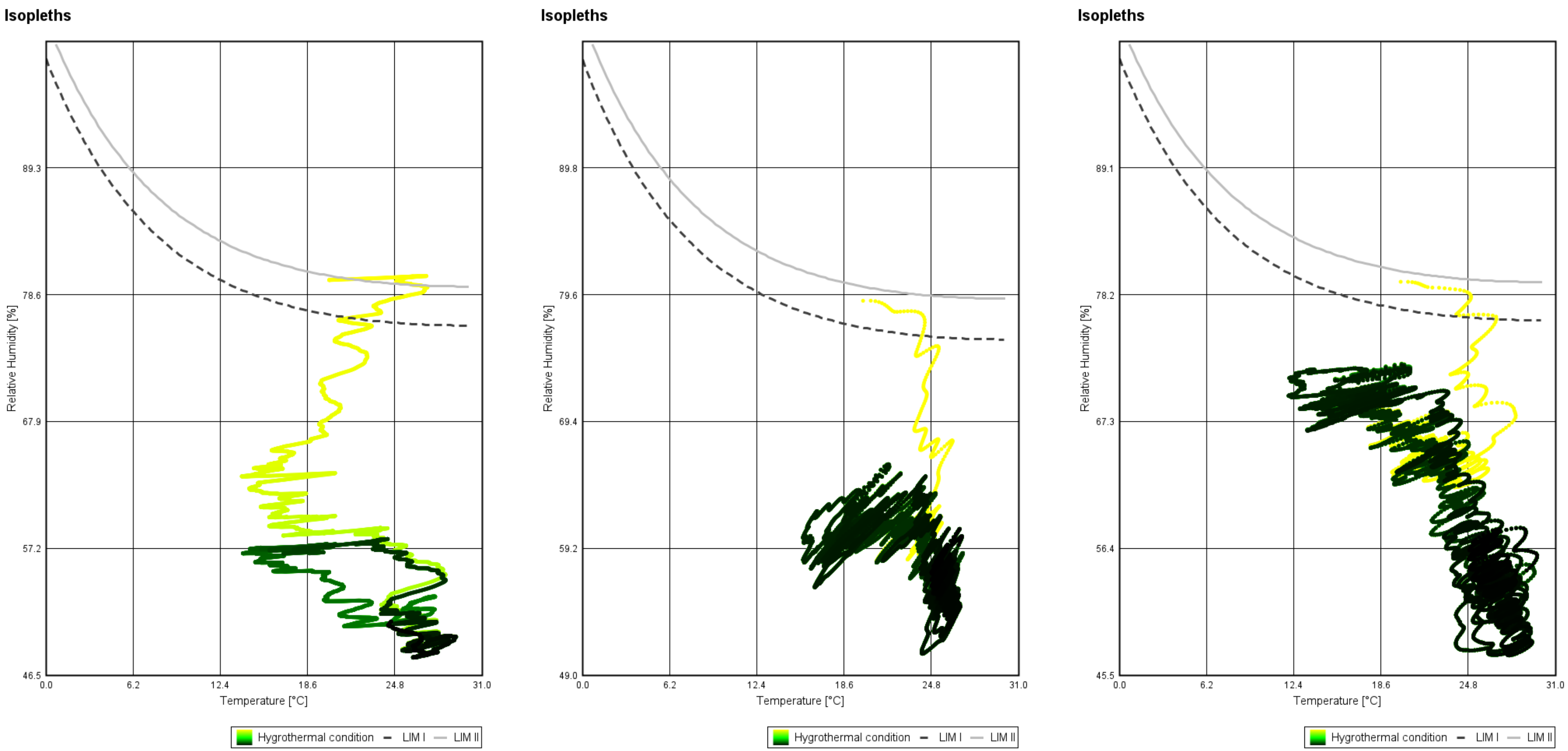


Figure 5-17 Hygrothermal Conditions in Walls W2CH (left), W8LS (middle) and W8MB (right).

W2CH (Camel's hair + Clay Plaster 350mm), W8LS (Limestone +Camel's hair insulation+ Clay Plaster 350mm), and W8MB (Mud Block+ Camel's hair insulation+ Clay Plaster 350mm-

- ***ASHRAE-160 Criterion;***

The ASHRAE -160 criteria for moisture control design analysis in buildings set the performance criteria to minimize moisture-associated issues in building envelope and components. The ASHRAE-16 specifies that the following conditions be met; “A30-day running average surface relative humidity (RH) should be less than 80% when the 30-day running average surface temperature is between 5◦C and 41◦C” [154].

The Figures below show the average 30 days temperature and RH in walls W2CH (Camel’s hair + Clay Plaster 350mm), Wall W8LS (Limestone +Camel’s hair insulation+ Clay Plaster 350mm), and Wall W8MB (Mud Block+ Camel’s hair insulation+ Clay Plaster 350mm). The walls' surface RH% and Temperature were averaged over 30 days and compared to ASHRAE -160 limits.

Since in all walls, the RH% is consistently below 80%, and the temperature is always above 10˚C, it can be said that all walls have passed the ASHRAE-160 criteria.

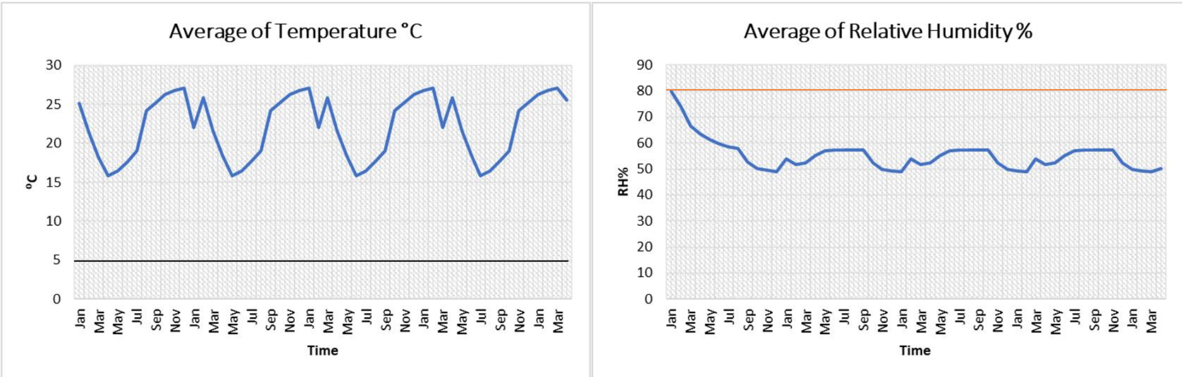


Figure 5-18 Average Temperature and Relative Humidity for Wall W2CH

W2CH (Camel’s hair + Clay Plaster 350mm)

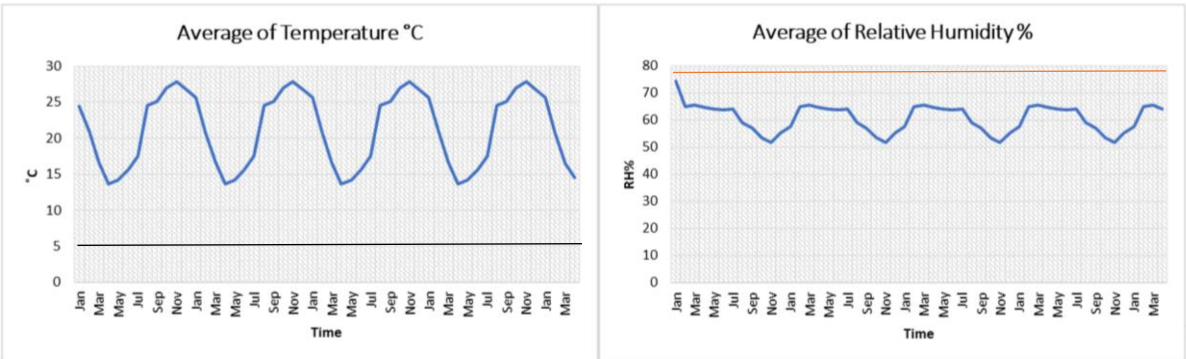
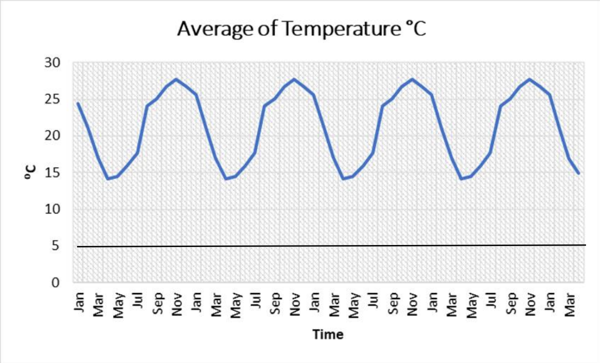


Figure 5-19 Average Temperature and Relative Humidity for Wall W8LS

W8LS (Limestone +Camel’s hair insulation+ Clay Plaster 350mm)



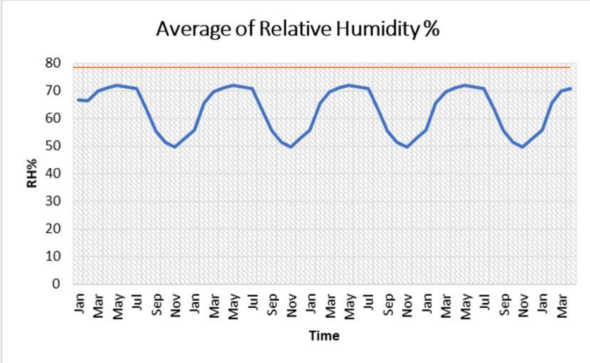


Figure 5-20 Average Temperature and Relative Humidity for Wall W8MB

W8MB (Mud Block+ Camel's hair insulation+ Clay Plaster 350mm)

5.2.5 Hygrothermal Simulations of Calibrated Case Study Models

This subsection will use the calibrated models of the Case Study Houses for the simulation in Design-Builder and WUFI Plus. The selected walls from the sensitivity analysis and the hygrothermal behaviour assessment will be applied to each Case Study House to study the impact of different wall choices on indoor temperature, relative humidity, hygrothermal comfort, and potential energy savings.

The selected wall assemblies from the sensitivity analysis are the hygrothermal behaviour assessment are:

- ***W2CH*** (Camel's hair + Clay Plaster 350mm)
- ***W8LS*** (Limestone +Camel hair insulation +Cement Plaster 350mm).
- ***W8MB*** (Mud Block +Camel hair insulation +Cement Plaster 350mm).

5.2.5.1 The Impact of Changing Wall Assembly on The Indoor Temperature and Relative Humidity

This section presents the simulation results of the Case Study Houses from Design-Builder and WUFI Plus. An example from each house representing cold and hot months (January and August) to show the impact of changing wall assembly on temperature and relative humidity is presented in the figures below. The annual simulation results and the impact of changing walls on the temperature and relative humidity of the Case Study Houses can be found in the Appendices.

- ***Case Study House 1 (January Results)***

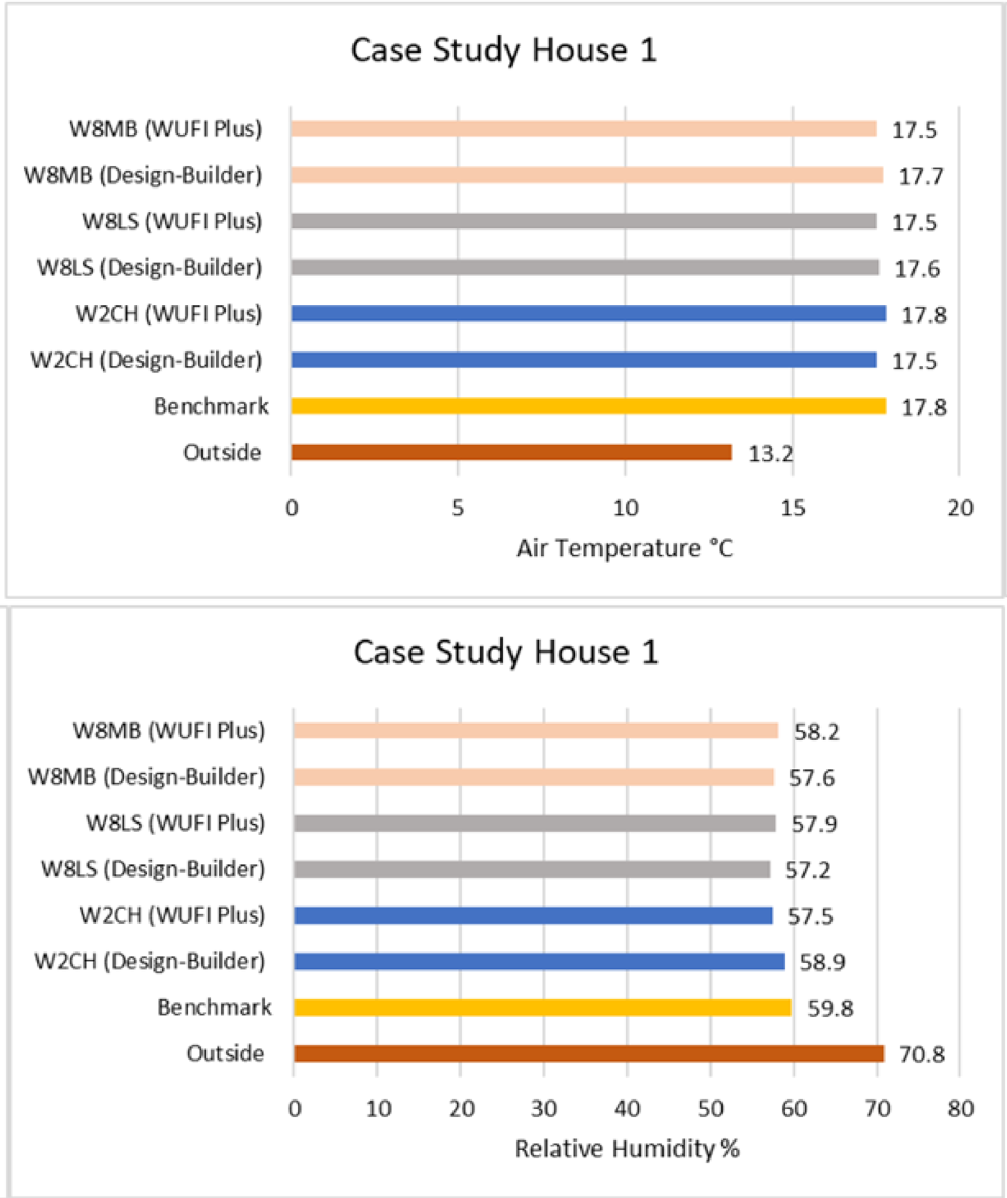


Figure 5-21 Impact of Changing Wall Assembly on the Average Hourly Indoor Temperature (Top) and Relative Humidity (Bottom) in Design-Builder and WUFI Plus (Case Study House 1-in January)

W2CH (Camel's hair + Clay Plaster 350mm), W8LS (Limestone +Camel's hair insulation+ Clay Plaster 350mm), and W8MB (Mud Block+ Camel's hair insulation+ Clay Plaster 350mm)

Figure 5-21 shows the impact of various wall assemblies on the temperature and relative humidity of Case Study House 1 in Design Builder and WUFI Plus during winter. A slight decrease in RH levels can be seen in the figure. The highest decrease is in Design Builders' result of wall W8LS (Limestone +Camel hair insulation +Cement Plaster 350mm) with around 2.6% decrease in indoor RH. Design-Builder and WUFI Plus results show no significant impact on the temperature of Case Study House 1 with any of the selected walls.

- ***Case Study House 1 (August Results)***

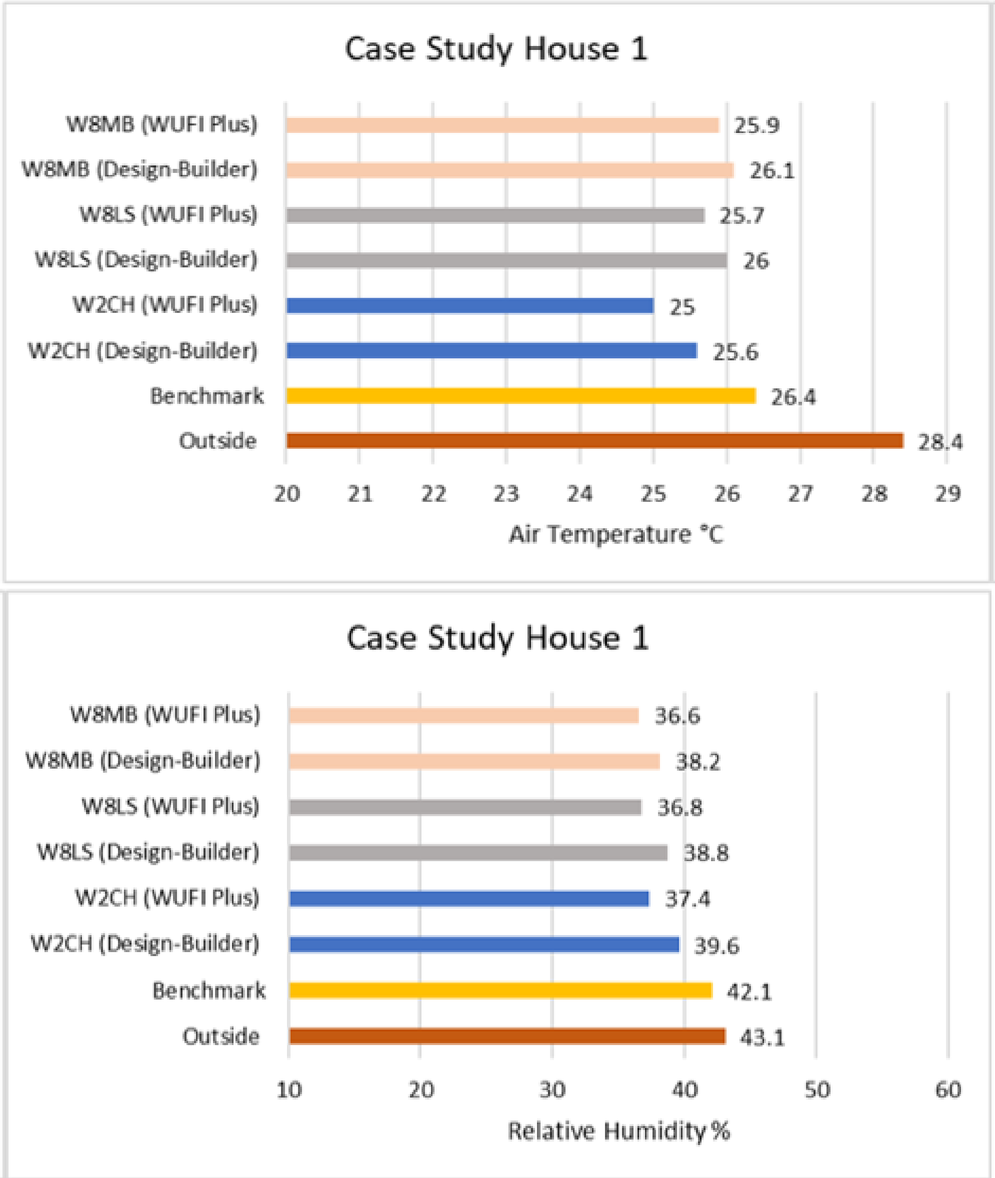


Figure 5-22 Impact of Changing Wall Assembly on the Average Hourly Indoor Temperature (Top) and Relative Humidity (Bottom) in Design-Builder and WUFI Plus (Case Study House 1- in August)
W2CH (Camel's hair + Clay Plaster 350mm), W8LS (Limestone +Camel's hair insulation+ Clay Plaster 350mm), and W8MB (Mud Block+ Camel's hair insulation+ Clay Plaster 350mm)

The summer simulation results, presented in Figure 5-22, showed that all walls were able to reduce the indoor temperature of Case Study House 1 in August. The relative humidity was also decreased in all cases.

The highest temperature reduction is in Wall W2CH (Camel's hair + Clay Plaster 350mm), with around 1.4°C in WUFI Plus and 0.8°C in Design-Builder's results. For wall W8LS (Limestone +Camel hair insulation +Cement Plaster 350mm), the temperature decreased by 0.7°C in WUFI Plus and 0.4°C in Design-Builder. The lowest temperature reduction is for wall W8MB (Mud Block +Camel hair insulation +Cement Plaster 350mm), as seen from the figure.

For relative humidity, a slight decrease in RH can be seen for all walls, with the highest RH reduction with wall W8LS (Limestone +Camel hair insulation +Cement Plaster 350mm) with around 6% in WUFI Plus and around 4% in Design-Builder results. The smallest reduction in RH for wall W2CH (Camel's hair + Clay Plaster 350mm). There was an agreement between the results from both software for all walls in terms of indoor RH, as Figure 5-22 above showed.

- ***Case Study House 2 (January Results)***

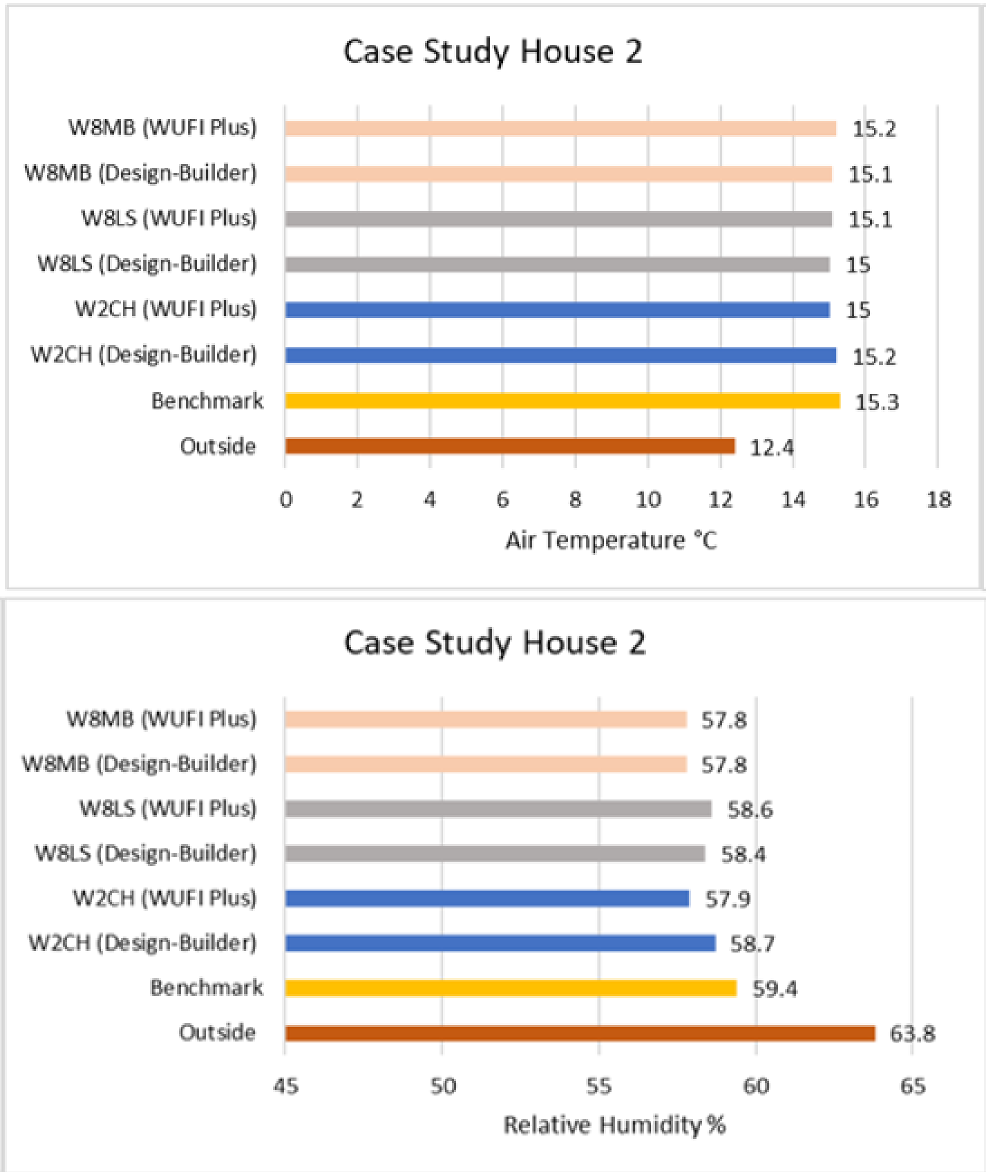


Figure 5-23 Impact of Changing Wall Assembly on the Average Hourly Indoor Temperature (Top) and Relative Humidity (Bottom) in Design-Builder and WUFI Plus (Case Study House-2 in January)
W2CH (Camel's hair + Clay Plaster 350mm), W8LS (Limestone +Camel's hair insulation+ Clay Plaster 350mm), and W8MB (Mud Block+ Camel's hair insulation+ Clay Plaster 350mm)

The Figure above shows the impact of applying the suggested walls on the air temperature and relative humidity of Case Study House 2 during winter. There is an agreement between Design-Builder and WUFI Plus results, as the Figure shows no significant impact on indoor temperature with any of the selected walls. The Figure also showed a minimal impact on indoor relative humidity during winter for all walls.

- ***Case Study House 2 (August Results)***

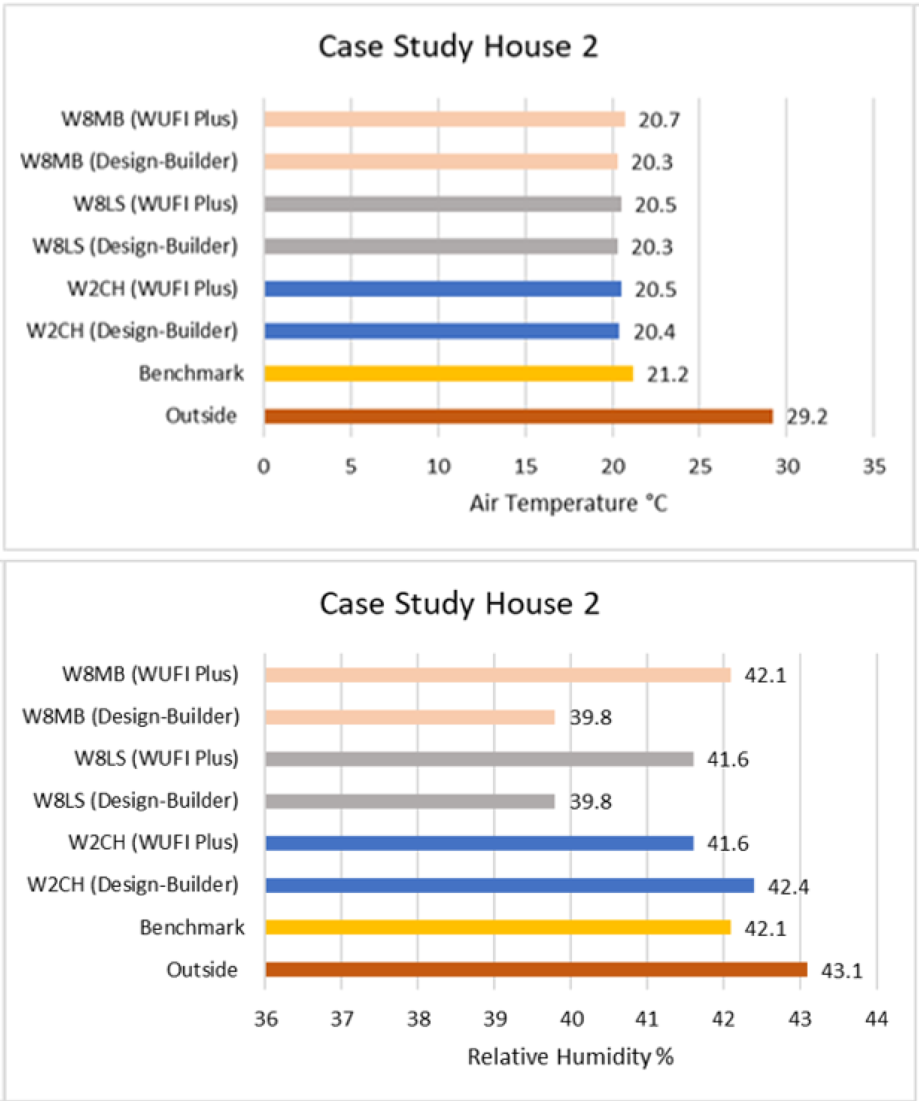


Figure 5-24 Impact of Changing Wall Assembly on the Average Hourly Indoor Temperature (Top) and Relative Humidity (Bottom) in Design-Builder and WUFI Plus (Case Study House-2 in August)
W2CH (Camel's hair + Clay Plaster 350mm), W8LS (Limestone +Camel's hair insulation+ Clay Plaster 350mm), and W8MB (Mud Block+ Camel's hair insulation+ Clay Plaster 350mm)

Figure 5-24 shows a summer simulation example for Case Study House 2. The temperature simulation results show that all walls could reduce indoor temperature. The figure showed that all walls had a similar impact on the indoor temperature, with an average reduction of around 0.8°C. As seen from the figure, there was no significant impact for any of the walls on the indoor RH.

- ***Case Study House 3 (January Results)***

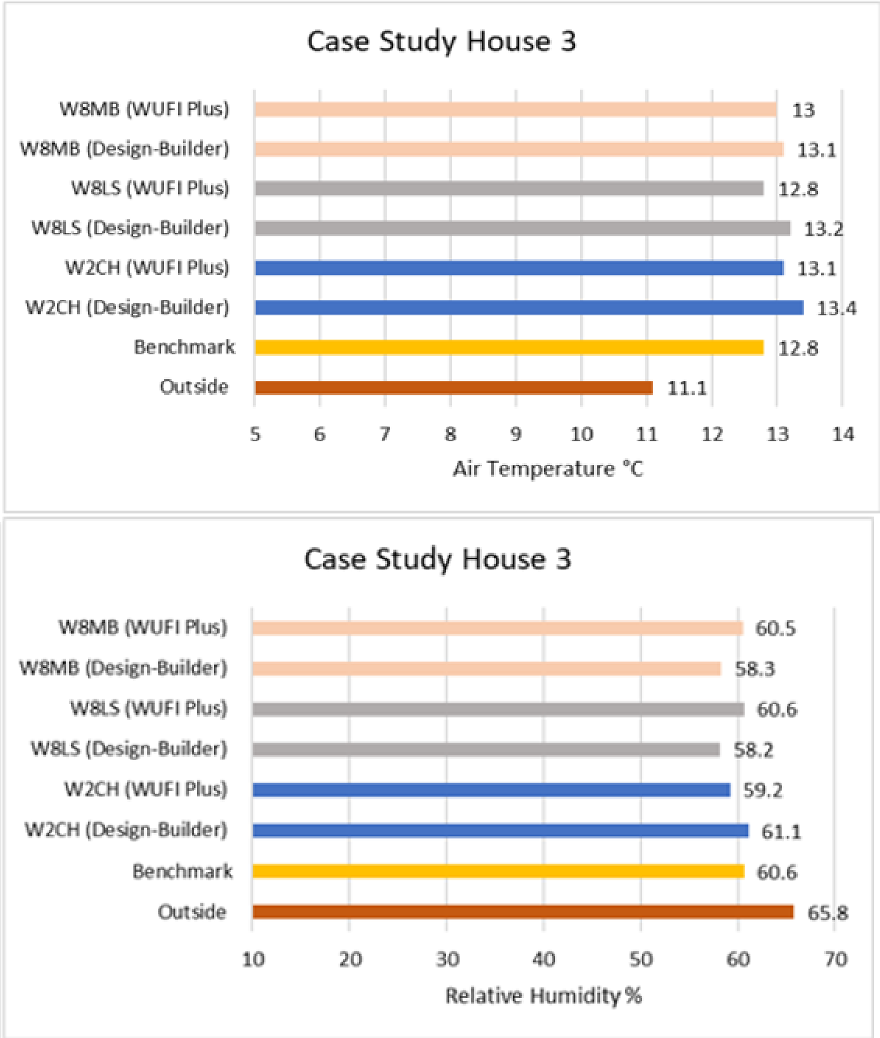


Figure 5-25 Impact of Changing Wall Assembly on the Average Hourly Indoor Temperature (Top) and Relative Humidity (Bottom) in Design-Builder and WUFI Plus (Case Study House-3 in January)
W2CH (Camel's hair + Clay Plaster 350mm), W8LS (Limestone +Camel's hair insulation+ Clay Plaster 350mm), and W8MB (Mud Block+ Camel's hair insulation+ Clay Plaster 350mm)

Winters simulation results for Case Study House 3 in Design-Builder and WUFI Plus are presented in Figure 5-25 above. No major impact on RH for any of all as can be seen from the figure. The indoor temperature increased in almost all cases during winter.

The highest increase in temperature is for wall W2CH (Camel's hair + Clay Plaster 350mm), with 0.6°C and 0.3°C in Design-Builder and WUFI Plus results, respectively. For wall W8LS (Limestone +Camel hair insulation +Clay Plaster 350mm), the results showed a 0.4°C and 0.0°C increase in Design-Builder and WUFI Plus, respectively. The results of wall W8MB (Mud Block +Camel hair insulation +Clay Plaster 350mm) were similar in Design-Builder and WUFI Plus with no change in indoor air temperature.

- ***Case Study House 3 (August Results)***

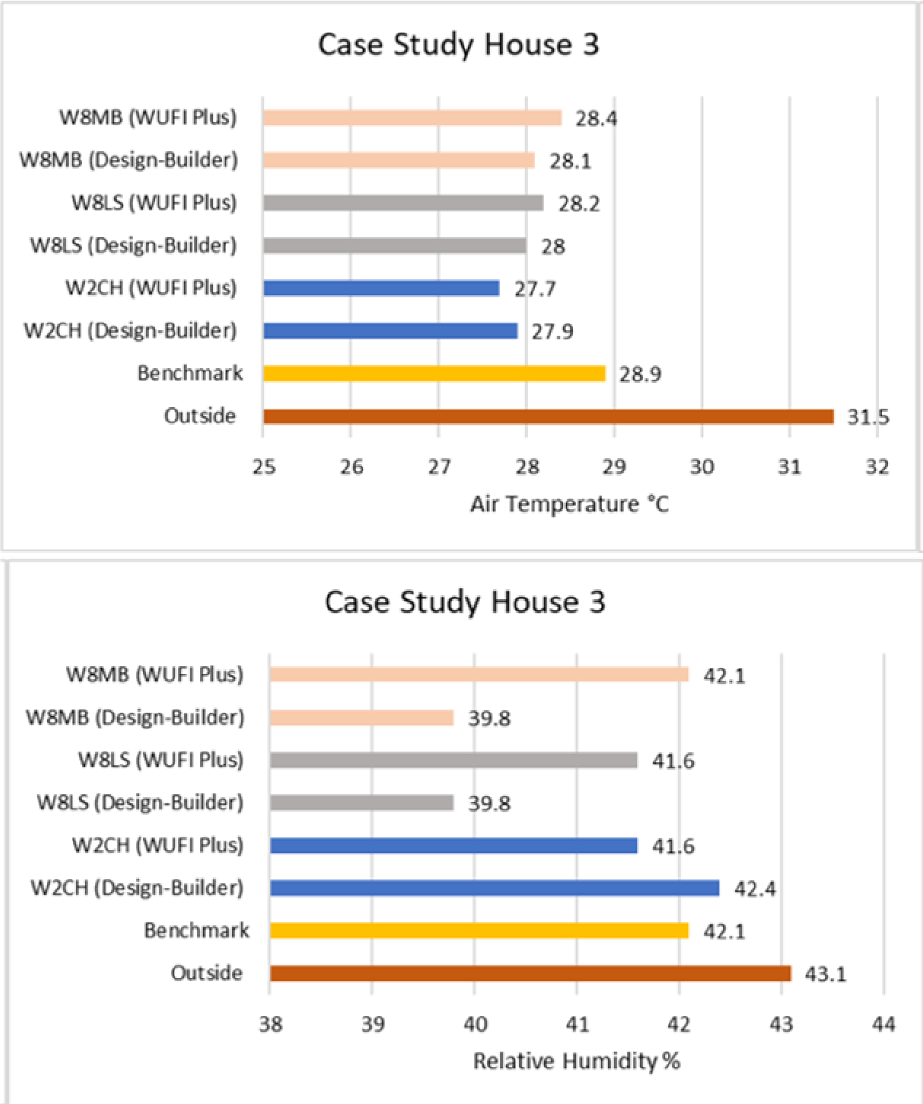


Figure 5-26 Impact of Changing Wall Assembly on the Average Hourly Indoor Temperature (Top) and Relative Humidity (Bottom) in Design-Builder and WUFI Plus (Case Study House-3 in August)

W2CH (Camel's hair + Clay Plaster 350mm), W8LS (Limestone +Camel's hair insulation+ Clay Plaster 350mm), and W8MB (Mud Block+ Camel's hair insulation+ Clay Plaster 350mm)

The Figure above presented the summer simulation results of Case Study House 3 in Design-Builder and WUFI Plus. The results indicate that all walls could reduce indoor air temperature during summer. There was little impact for all walls on the indoor RH.

The highest reduction in temperature can be seen for wall W2CH (Camel's hair + Clay Plaster 350mm) with around 1°C in Design-Builder and 1.2°C in WUFI Plus. The results from the other two walls are similar and show 0.8°C reductions in the temperature.

The simulations showed a higher impact for all walls on the summer's indoor temperature of the Case Study Houses compared to winter's temperature. A minimum impact on RH during summer and winter was noted for all walls. An average of around 1.2°C reductions was absorbed for all walls, which can lead to a significant decrease in cooling energy demands.

5.2.5.2 Hygrothermal Comfort Assessment.

The detailed methodology for the hygrothermal comfort assessment is in section 3.6.7.

The impact of wall choice on the hygrothermal comfort of the Case Study Houses is presented in this section. The hygrothermal comfort was assessed using the Predicted Mean Vote (PMV) and the Predicted Percentage of Dissatisfaction (PPD%).

In general, for the three Case Studies, the air velocity was estimated at 0.1 m/s, and a metabolic rate of 0.7 met was used for the bedrooms, and 1.0 met for the Living rooms of the Case Study Houses. Clo value of 1 was used for November-March, 0.74 for April and October, and 0.5 for May -September.

The simulations were performed in Design-Builder and WUFI Plus. An example from each Case Study to show the impact of different wall assemblies on hygrothermal comfort is presented here. the PPD and PMV results for the three Case Study Houses can be found in the Appendices.

5.2.5.2.1 Case Study House-1

The Predicted Mean Vote (PMV) and the Predicted Percentage of Dissatisfaction (PPD%) were calculated for the Living room and Bedrooms 1 and 2 of Case Study House 1. Below are the Living room PPD and PMV results from Design-Builder and WUFI Plus.

See the Appendices for Bedroom 1 and 2 PPD and PMV results.

- ***Living Room (Design-Builder Results)***

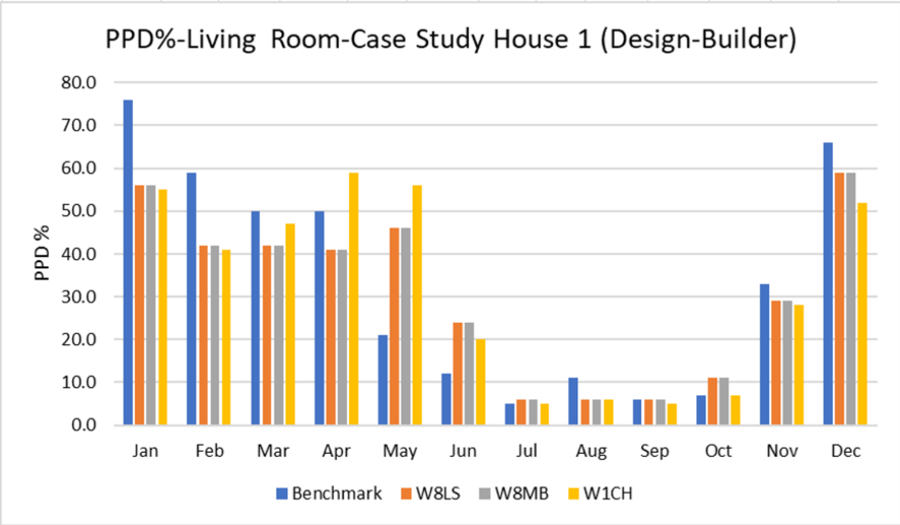
Table 5-26 below presents the PMV results from Design-Builder for the living room of Case Study House 1. The PPD% results for the Living room from Design-Builder are shown in Figure 5-27.

Table 5-26 PMV-Living Room-Case Study House-1 (Design-Builder)

W2CH (Camel's hair + Clay Plaster 350mm), W8LS (Limestone +Camel's hair insulation+ Clay Plaster 350mm), and W8MB (Mud Block+ Camel's hair insulation+ Clay Plaster 350mm)

Time	Benchmark		W8-LS		W8-MB		W2CH	
	PMV	Sensation	PMV	Sensation	PMV	Sensation	PMV	Sensation
Jan	-2.0	Cool	-1.6	Cool	-1.6	Cool	-1.6	Cool
Feb	-1.7	Cool	-1.3	S-Cool	-1.3	S-Cool	-1.3	S-Cool
Mar	-1.5	S-Cool	-1.3	S-Cool	-1.3	S-Cool	-1.4	S-Cool
Apr	-1.5	S-Cool	-1.3	S-Cool	-1.3	S-Cool	-1.6	Cool
May	-0.9	S-Cool	-1.4	S-Cool	-1.4	S-Cool	-1.6	Cool
Jun	-0.6	S-Cool	-1.0	S-Cool	-1.0	S-Cool	-0.9	S-Cool
Jul	0.0	Neutral	0.0	Neutral	0.0	Neutral	0.0	Neutral
Aug	0.5	S-Warm	0.0	Neutral	0.0	Neutral	0.2	Neutral
Sep	0.0	Neutral	0.0	Neutral	0.0	Neutral	0.1	Neutral
Oct	0.0	Neutral	-0.4	Neutral	-0.4	Neutral	-0.3	Neutral
Nov	-1.2	S-Cool	-1.0	S-Cool	-1.0	S-Cool	-1.0	S-Cool
Dec	-1.8	Cool	-1.6	Cool	-1.6	Cool	-1.5	Cool

Where; Cool=Cool, S-Cool= Slightly Cool, Neutral= Neutral, S-Warm= Slightly Warm, Warm= Warm.
Green colour indicates improvement, red colour indicates deterioration



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Benchmark	76	59	50	50	21	12	5	11	6	7	33	66
W8LS	**56**	**42**	**42**	**41**	**46**	**24**	**6**	**6**	6	**11**	**29**	**59**
W8MB	**56**	**42**	**42**	**41**	**46**	**24**	**6**	**6**	6	**11**	**29**	**59**
W2CH	**55**	**41**	**47**	**59**	**56**	**20**	5	**6**	5	7	**28**	**52**

Figure 5-27 PPD%-Living Room-Case Study House-1 (Design-Builder)

W2CH (Camel's hair + Clay Plaster 350mm), W8LS (Limestone +Camel's hair insulation+ Clay Plaster 350mm), and W8MB (Mud Block+ Camel's hair insulation+ Clay Plaster 350mm)

Green colour indicates improvement, red colour indicates deterioration

Table 5-26 and Figure 5-27 above show the PPD and PMV results of the Living room from Design-Builder. The figure and table above showed that the PMV and PPD% improve in some cases when changing the wall assembly. It can be seen from the table that walls W8LS (Limestone +Camel hair insulation +Clay Plaster 350mm), and W8MB (Mud Block +Camel hair insulation +Clay Plaster 350mm) are performing better than walls W2CH (Camel's hair + Clay Plaster 350mm) in providing hygrothermal comfort.

The table shows improvements in PMV for all walls in February and August. There was no change in the PMV of the remaining months for walls W8LS and W8MB. For wall W2CH, the PMV results are similar to the other two walls except for April and May, where the PMV declines from Slightly Cool to Cool during both months.

The PPD% results for the Living room are presented in Figure 5-27. The results show a decrease in PPD% for all walls in months from January-March, August, November, and December. PPD% slightly improved in April for wall W8LS and W8MB (from 50% -42%). From Figure 5-27, the PPD% increased for all walls during April, May, June, and October, which might be due to improved thermal insulation of walls W8LS, W8MB and W2CH compared to the original wall, resulting in a slight decrease in the Living room temperature.

For this case, the PMV and PPD% results of the living room of Case Study House 1 in Design-Builder indicate that Walls W8LS and W8MB are performing better than wall W2CH.

- ***Living room (WUFI Plus Results)***

Table 5-27 presents the PMV results from WUFI Plus for the Living room of Case Study House 1. The PPD% results for the Living room from WUFI Plus are shown in Figure 5-28 below.

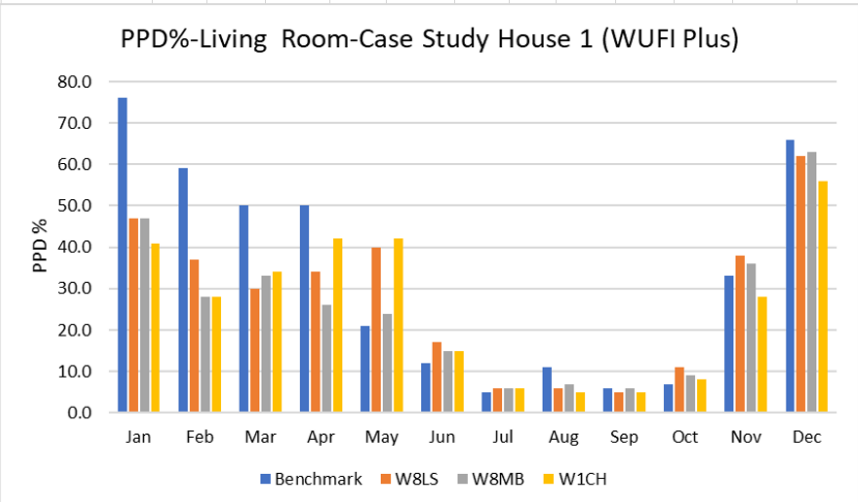
Table 5-27 PMV-Living Room-Case Study House 1 (WUFI Plus)

W2CH (Camel's hair + Clay Plaster 350mm), W8LS (Limestone +Camel's hair insulation+ Clay Plaster 350mm), and W8MB (Mud Block+ Camel's hair insulation+ Clay Plaster 350mm)

Time	Benchmark		W8-LS		W8-MB		W2CH	
	PMV	Sensation	PMV	Sensation	PMV	Sensation	PMV	Sensation
Jan	-2.0	Cool	-1.4	**S-Cool**	-1.4	**S-Cool**	-1.3	**S-Cool**
Feb	-1.7	Cool	-1.3	**S-Cool**	-1.0	**S-Cool**	-1.1	**S-Cool**
Mar	-1.5	S-Cool	-1.3	S-Cool	-1.2	S-Cool	-1.2	S-Cool
Apr	-1.5	S-Cool	-1.4	S-Cool	-1.0	S-Cool	-1.3	S-Cool
May	-0.9	S-Cool	-1.0	S-Cool	-1.0	S-Cool	-1.3	S-Cool
Jun	-0.6	S-Cool	0.0	**Neutral**	-0.7	S-Cool	-0.7	S-Cool
Jul	0.0	Neutral	0.0	Neutral	0.0	Neutral	0.2	Neutral
Aug	0.5	S-Warm	0.0	**Neutral**	0.0	**Neutral**	0.1	**Neutral**
Sep	0.0	Neutral	-0.5	Neutral	0.0	Neutral	0.0	Neutral
Oct	0.0	Neutral	0.0	Neutral	0.0	Neutral	-0.4	Neutral
Nov	-1.2	S-Cool	-1.1	S-Cool	-1.2	S-Cool	-1.0	S-Cool
Dec	-1.8	Cool	-1.6	Cool	-1.7	Cool	-1.6	Cool

Where; Cool=Cool, S-Cool= Slightly Cool, Neutral= Neutral, S-Warm= Slightly Warm, Warm= Warm.

Green colour indicates improvement, red colour indicates deterioration



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Benchmark	76	59	50	50	21	12	5	11	6	7	33	66
W8LS	**47**	**37**	**30**	**34**	**40**	**17**	**6**	**6**	**5**	**11**	**38**	**62**
W8MB	**47**	**28**	**33**	**26**	**24**	**15**	**6**	**7**	6	**9**	**36**	**63**
W2CH	**41**	**28**	**34**	**42**	**42**	**15**	**6**	**5**	**5**	**8**	28	**56**

Figure 5-28 PPD%-Living Room-Case Study House 1 (WUFI Plus)

W2CH (Camel's hair + Clay Plaster 350mm), W8LS (Limestone +Camel's hair insulation+ Clay Plaster 350mm), and W8MB (Mud Block+ Camel's hair insulation+ Clay Plaster 350mm)

Green colour indicates improvement, red colour indicates deterioration

Table 5-27 shows that the thermal sensation improves in many cases with all walls. The Table showed that the PMV improved in January and February from Cool to Slightly Cool for all walls. In June, the PMV improved from Slightly Cool to Neutral for wall W8LS (Limestone +Camel hair insulation +Clay Plaster 350mm), and in August, the PMV improved from Slightly Warm to Neutral for all walls. For the remaining months, the PMV for all walls is the same as Benchmark's PMV. This is slightly different from Design-Builder's results.

Figure 5-28 show the PPD% results. The figure shows a considerable reduction in the PPD% for all walls. More notably, in January and August for wall W2CH (from 76%-41% in January and from 11% - 5% in August). Similar to Design-Builder results, the PPD% decreases in winter but increases during summer, again due to decreased indoor temperature caused by improved insulation properties of the suggested walls compared to the Benchmark wall. (See Appendix A5 for indoor temperature details).

5.2.5.2.2 Case Study House 2

The Predicted Mean Vote (PMV) and the Predicted Percentage of Dissatisfaction (PPD%) were calculated for the Living room and the Main Bedroom of Case Study House 2. Below are the Living room PPD and PMV results from Design-Builder and WUFI Plus. The PPD-PMV for the Main bedroom are in the Appendices.

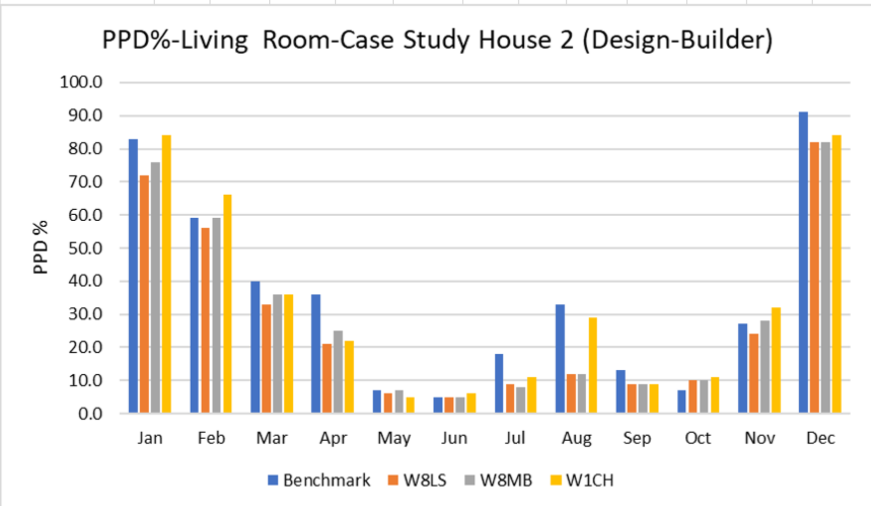
- ***Living Room (Design-Builder Results)***

Table 5-28 PMV-Living Room-Case Study House-2 (Design-Builder)

W2CH (Camel's hair + Clay Plaster 350mm), W8LS (Limestone +Camel's hair insulation+ Clay Plaster 350mm), and W8MB (Mud Block+ Camel's hair insulation+ Clay Plaster 350mm)

Time	Benchmark		W8LS		W8MB		W2CH	
	PMV	Sensation	PMV	Sensation	PMV	Sensation	PMV	Sensation
Jan	-2.1	Cool	-1.9	Cool	-2.0	Cool	-2.0	Cool
Feb	-1.8	Cool	-1.6	Cool	-1.7	Cool	-1.7	Cool
Mar	-1.5	S-Cool	-1.3	S-Cool	-1.3	S-Cool	-1.3	S-Cool
Apr	-1.2	S-Cool	-0.9	S-Cool	-1.0	S-Cool	-1.0	S-Cool
May	0.0	Neutral	0.0	Neutral	0.0	Neutral	0.0	Neutral
Jun	0.6	S-Warm	0.0	**Neutral**	0.0	**Neutral**	0.0	**Neutral**
Jul	-1.1	S-Warm	0.7	S-Warm	0.8	S-Warm	0.8	S-Warm
Aug	1.5	S-Warm	0.9	S-Warm	0.9	S-Warm	0.9	S-Warm
Sep	0.8	S-Warm	0.6	S-Warm	0.7	S-Warm	0.7	S-Warm
Oct	0.0	Neutral	0.0	Neutral	0.0	Neutral	0.0	Neutral
Nov	-1.1	S-Cool	-1.0	S-Cool	-1.1	S-Cool	-1.1	S-Cool
Dec	-2.4	Cool	-2.1	Cool	-2.2	Cool	-2.2	Cool

Where; Cool=Cool, S-Cool= Slightly Cool, Neutral= Neutral, S-Warm= Slightly Warm, Warm= Warm.
Green colour indicates improvement, red colour indicates deterioration



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Benchmark	83	59	40	36	7	5	18	33	13	7	27	91
W8LS	72	56	33	21	6	5	9	12	9	10	24	82
W8MB	76	59	36	25	7	5	8	12	9	10	28	82
W2CH	79	63	40	28	5	8	12	14	11	8	27	86

Figure 5-29 PPD%-Living Room-Case Study House-2 (Design-Builder)

W2CH (Camel's hair + Clay Plaster 350mm), W8LS (Limestone +Camel's hair insulation+ Clay Plaster 350mm), and W8MB (Mud Block+ Camel's hair insulation+ Clay Plaster 350mm)

Green colour indicates improvement, red colour indicates deterioration

Table 5-28 and Figure 5-42 show the PPD% and PMV results for the Living room of Case Study House 2 in Design-Builder.

Table 5-13 shows that the PMV improves in June from Slightly Warm to Neutral for all walls. The PMV remain unchanged for the remaining months for all walls. Figure 5-29 shows that the PPD% decreased with all walls compared to the Benchmark wall. It can be seen from the figure that wall W8LS (Limestone +Camel hair insulation +Clay Plaster 350mm) is performing better than the other two walls in terms of providing thermal comfort for the Living room of Case Study House 2.

- ***Living Room (WUFI Plus)***

Table 5-29 PMV-Living Room-Case Study House-2 (WUFI Plus)

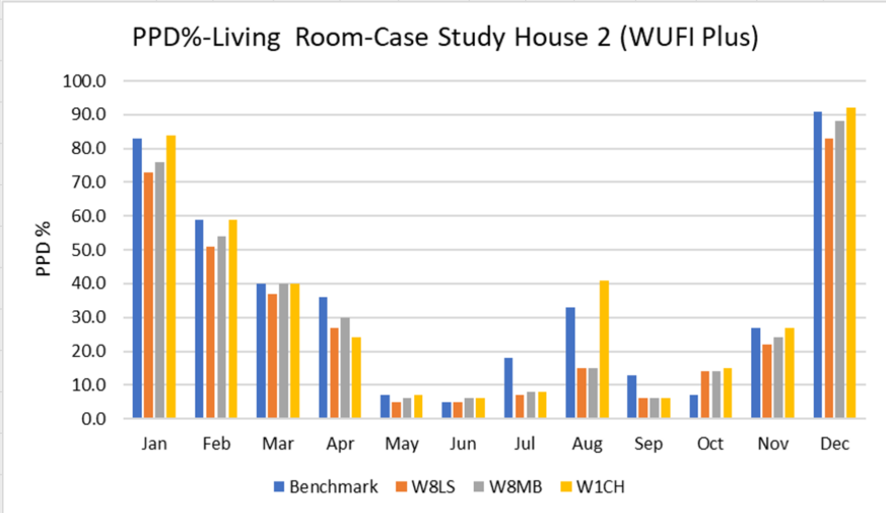
W2CH (Camel's hair + Clay Plaster 350mm), W8LS (Limestone +Camel's hair insulation+ Clay Plaster 350mm), and W8MB (Mud Block+ Camel's hair insulation+ Clay Plaster 350mm)

Time	Benchmark		W8-LS		W8-MB		W2CH	
	PMV	Sensation	PMV	Sensation	PMV	Sensation	PMV	Sensation
Jan	-2.1	Cool	-2.0	Cool	-2.0	Cool	-2.0	Cool
Feb	-1.8	Cool	-1.6	Cool	-1.7	Cool	-1.6	Cool
Mar	-1.5	S-Cool	-1.5	S-Cool	-1.5	S-Cool	-1.5	S-Cool
Apr	-1.2	S-Cool	-1.1	S-Cool	-1.1	S-Cool	-1.1	S-Cool
May	0.0	Neutral	0.0	Neutral	0.0	Neutral	0.0	Neutral
Jun	0.6	S-Warm	0.0	**Neutral**	0.0	**Neutral**	0.0	**Neutral**
Jul	-1.1	S-Warm	0.7	S-Warm	0.7	S-Warm	0.7	S-Warm
Aug	1.5	S-Warm	-1.1	S-Warm	-1.1	S-Warm	-1.1	S-Warm

Sep	0.8	S-Warm	0.5	S-Warm	0.5	S-Warm	0.5	S-Warm
Oct	0.0	Neutral	0.0	Neutral	0.0	Neutral	0.0	Neutral
Nov	-1.1	S-Cool	-1.0	S-Cool	-1.0	S-Cool	-1.0	S-Cool
Dec	-2.4	Cool	-2.3	Cool	-2.3	Cool	-2.3	Cool

Where; Cool=Cool, S-Cool= Slightly Cool, Neutral= Neutral, S-Warm= Slightly Warm, Warm= Warm.

Green colour indicates improvement, red colour indicates deterioration



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Benchmark	83	59	40	36	7	5	18	33	13	7	27	91
W8LS	73	51	37	27	5	5	7	15	6	14	22	83
W8MB	76	54	40	30	6	6	8	15	6	14	24	88
W2CH	77	55	42	29	6	5	11	20	9	10	28	88

Figure 5-30 PPD%-Living Room-Case Study House-2 (WUFI Plus)

W2CH (Camel's hair + Clay Plaster 350mm), W8LS (Limestone +Camel's hair insulation+ Clay Plaster 350mm), and W8MB (Mud Block+ Camel's hair insulation+ Clay Plaster 350mm)

Green colour indicates improvement, red colour indicates deterioration

Table 5-29 and Figure 5-30 show the PMV-PPD% for the living room of Case Study House 2 in WUFI Plus. The results show an improvement in the PMV in June for all walls. For the remaining months, the PMV remains unchanged. From the figure, it can be seen that the PPD% decreased with all walls. A slight increase in PPD% can be seen for wall W2CH in March (from 40% to 42%), in October (from 7% to 10%), and in November (from 27% to 28%). A slight increase was also noted for wall W8LS in October and W8MB in March and October, with just a 3% average increase with both walls. The WUFI Plus results clearly show that all walls could improve the hygrothermal comfort of the living room of Case Study House 2.

5.2.5.2.3 Case Study House 3 (Free Running)

The Predicted Mean Vote (PMV) and the Predicted Percentage of Dissatisfaction (PPD%) were calculated for the Living room, Bedroom 1 and Lounge of Case Study House 3. Below are the Living room PPD and PMV results from Design-Builder and WUFI Plus. The PPD-PMV for Bedroom 1 and the Lounge are in Appendix A4.

- ***Living Room (Design-Builder)***

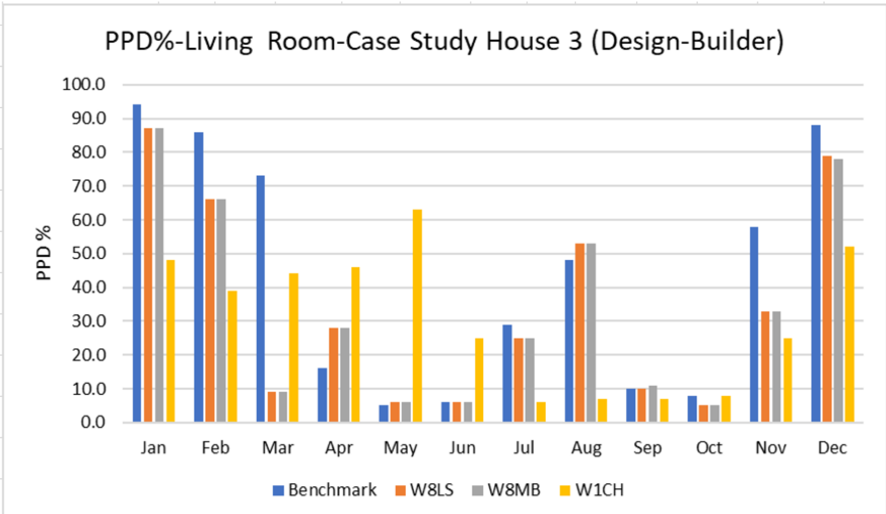
Table 5-30 PMV-Living Room-Case Study House-3 (Design-Builder)

W2CH (Camel's hair + Clay Plaster 350mm), W8LS (Limestone +Camel's hair insulation+ Clay Plaster 350mm), and W8MB (Mud Block+ Camel's hair insulation+ Clay Plaster 350mm)

Time	Benchmark		W8-LS		W8-MB		W2CH	
	PMV	Sensation	PMV	Sensation	PMV	Sensation	PMV	Sensation
Jan	-2.5	Cold	-2.3	Cool	-2.2	Cool	-2.6	Cool
Feb	-2.2	Cool	-1.8	Cool	-1.9	Cool	-1.9	Cool
Mar	-2.0	Cool	0.0	Neutral	0.0	Neutral	-1.2	S-Cool
Apr	-0.7	S-Cool	-1.0	S-Cool	-1.0	S-Cool	-1.3	S-Cool
May	0.0	Neutral	0.0	Neutral	0.0	Neutral	0.0	Neutral
Jun	0.0	Neutral	0.0	Neutral	0.0	Neutral	0.0	Neutral
Jul	1.1	S-Warm	1.0	S-Warm	1.0	S-Warm	1.1	S-Warm
Aug	1.5	S-Warm	1.4	S-Warm	1.4	S-Warm	1.6	Warm
Sep	0.5	Neutral	0.5	Neutral	0.5	Neutral	0.5	Neutral
Oct	0.0	Neutral	0.0	Neutral	0.0	Neutral	0.0	Neutral
Nov	-1.6	Cool	-1.0	S-Cool	-1.1	S-Cool	-1.4	S-Cool
Dec	-2.3	Cool	-2.0	Cool	-2.0	Cool	-2.3	Cool

Where; Cool=Cool, S-Cool= Slightly Cool, Neutral= Neutral, S-Warm= Slightly Warm, Warm= Warm.

Green colour indicates improvement, red colour indicates deterioration



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Benchmark	94	86	73	16	5	6	29	48	10	8	58	88
W8LS	87	66	9	28	6	6	25	53	10	5	33	79
W8MB	87	66	9	28	6	6	25	53	10	5	33	78
W2CH	89	74	21	38	5	6	25	57	9	6	40	85

Figure 5-31 PPD%-Living Room-Case Study House-3 (Design-Builder)

W2CH (Camel's hair + Clay Plaster 350mm), W8LS (Limestone +Camel's hair insulation+ Clay Plaster 350mm), and W8MB (Mud Block+ Camel's hair insulation+ Clay Plaster 350mm)

Green colour indicates improvement, red colour indicates deterioration

Table 5-30 and Figure 5-31 show the PMV-PPD% of the Living room of Case Study House 3. The PMV and PPD% results showed improvement in many Cases with all walls.

It can be seen from Table 5-30 that the PMV improves from Cold to Cool and from Cool to Neutral for all walls in January and March, respectively. November PMV also improved from Cool to Slightly Cool for all walls. The PPD%, shown in Figure 5-31, decreased in the following months; January to March, July, and October - December. The highest decrease in PPD% is for wall W8LS (Limestone +Camel hair insulation +Clay Plaster 350mm) and W8MB (Mud Block +Camel hair insulation +Clay Plaster 350mm). The results from Design-Builder clearly show that all the suggested walls can provide better hygrothermal comfort for Case Study 3 compared to the Benchmark wall.

- ***Living Room (WUFI Plus)***

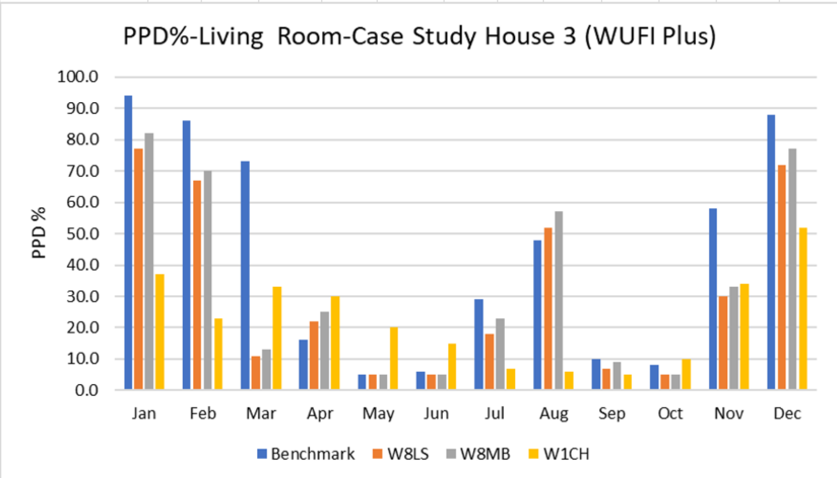
Table 5-31 PMV-Living Room-Case Study House 3 (WUFI Plus)

W2CH (Camel's hair + Clay Plaster 350mm), W8LS (Limestone +Camel's hair insulation+ Clay Plaster 350mm), and W8MB (Mud Block+ Camel's hair insulation+ Clay Plaster 350mm)

Time	Benchmark		W8-LS		W8-MB		W2CH	
	PMV	Sensation	PMV	Sensation	PMV	Sensation	PMV	Sensation
Jan	-2.5	Cold	-2.2	Cool	-2.2	Cool	-2.3	Cool
Feb	-2.2	Cool	-1.8	Cool	-1.8	Cool	-1.9	Cool
Mar	-2.0	Cool	0	Neutral	0	Neutral	-0.9	S-Cool
Apr	-0.7	S-Cool	-1	S-Cool	-1	S-Cool	1.2	S-Cool
May	0.0	Neutral	0	Neutral	0	Neutral	0	Neutral
Jun	0.0	Neutral	0	Neutral	0	Neutral	0	Neutral
Jul	1.1	S-Warm	1	S-Warm	1	S-Warm	1.1	S-Warm
Aug	1.5	S-Warm	1.5	S-Warm	1.5	S-Warm	1.6	Warm
Sep	0.5	Neutral	0.5	Neutral	0.5	Neutral	0.5	Neutral
Oct	0.0	Neutral	0	Neutral	0	Neutral	0	Neutral
Nov	-1.6	Cool	-1	S-Cool	-1	S-Cool	-1.3	S-Cool
Dec	-2.3	Cool	-2	Cool	-2	Cool	-2.3	Cool

Where; Cool=Cool, S-Cool= Slightly Cool, Neutral= Neutral, S-Warm= Slightly Warm, Warm= Warm.

Green colour indicates improvement, red colour indicates deterioration



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Benchmark	94	86	73	16	5	6	29	48	10	8	58	88
W8LS	77	67	11	22	5	5	18	52	7	5	30	72
W8MB	82	70	13	25	5	5	23	57	9	5	33	77
W2CH	85	77	33	28	5	5	22	60	10	5	44	80

Figure 5-32 PPD%-Living Room-Case Study House-3 (Design-Builder)

W2CH (Camel's hair + Clay Plaster 350mm), W8LS (Limestone +Camel's hair insulation+ Clay Plaster 350mm), and W8MB (Mud Block+ Camel's hair insulation+ Clay Plaster 350mm)

Green colour indicates improvement, red colour indicates deterioration

The figure and table Above show the PPD% and PMV results for the Living room of Case Study House 3 in WUFI Plus. The results from WUFI Plus are similar to those from Design-Builder, confirming the selected walls' ability to provide better hygrothermal comfort than the original wall. The results from both software show that wall W8LS W8LS (Limestone +Camel hair insulation +Clay Plaster 350mm) provides better hygrothermal comfort for Case Study 3 than the other two walls.

5.2.5.3 Energy Saving Potentials

The results presented here are for Case Studies 1 and 2, as Case Study House 3 is a free-running house with no active heating or cooling.

5.2.5.3.1 Case Study House-1

The calibrated model of Case Study House 1 was used for the simulation in WUFI Plus and Design-Builder using the same parameters and weather file used for the calibration (section 5.1). The simulation results of Case Study House 1 are presented in the Tables below.

a) Total Cooling (kWh)

Table 5-32 Total Cooling Energy Savings (kWh) and Percentage (%)

W2CH (Camel's hair + Clay Plaster 350mm), W8LS (Limestone +Camel's hair insulation+ Clay Plaster 350mm), and W8MB (Mud Block+ Camel's hair insulation+ Clay Plaster 350mm)

Time	Benchmark (kWh)	Total Cooling (kWh)					
		Design-Builder Results			WUFI Plus Results		
		W8LS	W8MB	W2CH	W8LS	W8MB	W2CH
Jan	0.0	0%	0%	0%	0%	0%	0%
Feb	0.0	0%	0%	0%	0%	0%	0%
Mar	0.0	0%	0%	0%	0%	0%	0%
Apr	12.4±0	75%	70%	67%	0%	0%	0%
May	448.4±93	60%	53%	50%	37%	37%	33%
Jun	604.7±19	58%	54%	51%	19%	19%	16%
Jul	632.8±8	58%	53%	50%	31%	30%	24%
Aug	807.7±44	58%	54%	51%	38%	36%	29%
Sep	392.4±25	58%	53%	50%	46%	44%	35%
Oct	467.1±2	63%	57%	54%	46%	45%	38%
Nov	0.0	0%	0%	0%	0%	0%	0%
Dec	0.0	0%	0%	0%	0%	0%	0%

Table 5-32 above shows the simulation results for the total cooling of Case Study House 1 in Design-Builder and WUFI Plus. The simulation from both software showed considerable cooling energy saving for Case Study House 1 for all walls. The highest cooling energy saving potential is for wall W8LS (Limestone +Camel hair insulation +Clay Plaster 350mm), as seen from the table.

Design-Builder results showed that in April, there is a potential of saving up to 75% of cooling energy with wall W8LS (Limestone +Camel hair insulation +Clay Plaster 350mm). The results also show potential cooling energy savings with 60% in May, 58% in June, July, August, and September, and up to 63% in October. WUFI Plus results for wall W8LS (Limestone +Camel hair insulation +Clay Plaster

350mm) showed a potential of 37% energy savings in May, 19% in June, 31% in July, 38% in August, and 46% in September and November.

For wall W8MB (Mud Block +Camel hair insulation +Clay Plaster 350mm), Design-Builder results showed a potential energy savings of up to 70% in April, 35% in May, and around 53% in June, July, August, September and October. In WUFI Plus, the results show potential for saving cooling energy with up to 37% in May, 19% in June, 30% in July, 36% in August, 44% in September and 45% in October.

For wall W2CH (Camel's hair + Clay Plaster 350mm), Design-Builder results showed a potential of saving up to 67% cooling energy in April and up to 52% energy savings for months from May to October. In WUFI Plus, the energy savings for wall W2CH are; 33% in May, 16% in June, 24% in July, 29% in August, 35% in September, and 38% in October.

b) Sensible Cooling (kWh)

Table 5-33 Sensible Cooling Energy Savings (kWh) and Percentage (%)

W2CH (Camel's hair + Clay Plaster 350mm), W8LS (Limestone +Camel's hair insulation+ Clay Plaster 350mm), and W8MB (Mud Block+ Camel's hair insulation+ Clay Plaster 350mm)

Time	Benchmark (kWh)	Sensible Cooling (kWh)					
		Design-Builder			WUFI Plus		
		W8LS	W8MB	W2CH	W8LS	W8MB	W2CH
Jan	0	0%	0%	0%			
Feb	0	0%	0%	0%			
Mar	0	0%	0%	0%			
Apr	0	0%	0%	0%			
May	357.7	54%	48%	46%			
Jun	427.2	53%	42%	43%			
Jul	494.0	46%	41%	38%			
Aug	668.4	31%	29%	25%			
Sep	249.7	39%	34%	33%			
Oct	276.9	77%	70%	68%			
Nov	0	0%	0%	0%			
Dec	0	0%	0%	0%			

The Table above presents the sensible cooling energy simulation results for Case Study House 1. The results in Table 5-33 are from Design-Builder only, as these were not available in WUFI Plus simulation reports. The table above shows that the amount of energy required for cooling the indoor air can be reduced using the suggested walls. The highest energy saving potentials are for wall W8LS (Limestone +Camel hair insulation +Clay Plaster 350mm), with around 31% energy saving in August (the hottest month) compared to 29% for W8MB (Mud Block +Camel hair insulation +Clay Plaster 350mm) and 25% for W2CH (Camel hair +Clay Plaster 350mm).

c) Zone Heating (kWh)

Table 5-34 Zone Heating Energy Savings (kWh) and Percentage (%)

W2CH (Camel's hair + Clay Plaster 350mm), W8LS (Limestone +Camel's hair insulation+ Clay Plaster 350mm), and W8MB (Mud Block+ Camel's hair insulation+ Clay Plaster 350mm)

Time	Benchmark (kWh)	Zone Heating (kWh)					
		Design-Builder Results			WUFI Plus Results		
		W8LS	W8MB	W2CH	W8LS	W8MB	W2CH
Jan	674.3±49	23%	17%	16%	26%	23%	18%
Feb	651.9±52	28%	21%	20%	26%	22%	20%
Mar	543.8±15	36%	31%	24%	37%	34%	28%
Apr	452.3±18	48%	40%	42%	53%	45%	38%
May	0.0	0%	0%	0%	0%	0%	0%
Jun	0.0	0%	0%	0%	0%	0%	0%
Jul	0.0	0%	0%	0%	0%	0%	0%
Aug	0.0	0%	0%	0%	0%	0%	0%
Sep	0.0	0%	0%	0%	0%	0%	0%
Oct	0.0	0%	0%	0%	0%	0%	0%
Nov	33.6±5	29%	23%	23%	0%	0%	0%
Dec	634.7±33	19%	14%	13%	34%	32%	29%

Table 5-34 above shows the simulation results of zone heating energy from Design-Builder and WUFI Plus. The table shows significant energy-saving potential for all walls. The highest heating energy saving potential in Design-Builder and WUFI Plus is for wall W8LS (Limestone +Camel hair insulation +Clay Plaster 350mm) compared to the other two walls.

5.2.5.3.2 Case Study House-2

The calibrated model of Case Study House 2 was used for the simulation in WUFI Plus and Design-Builder using the same parameters and weather file used for the calibration (section 5.1). The simulation results of Case Study House 2 are presented in the Tables below.

a) Total Cooling (kWh)

Table 5-35 Total Cooling Energy Savings (kWh) and Percentage (%)

W2CH (Camel's hair + Clay Plaster 350mm), W8LS (Limestone +Camel's hair insulation+ Clay Plaster 350mm), and W8MB (Mud Block+ Camel's hair insulation+ Clay Plaster 350mm)

Time	Benchmark (kWh)	Total Cooling [kWh]					
		Design-Builder			WUFI Plus		
		W8LS	W8MB	W2CH	W8LS	W8MB	W2CH
Jan	0.0	0%	0%	0%	0%	0%	0%
Feb	0.0	0%	0%	0%	0%	0%	0%
Mar	0.0	0%	0%	0%	0%	0%	0%
Apr	0.0	0%	0%	0%	0%	0%	0%
May	526.0±15	35%	33%	30%	33%	34%	31%
Jun	686.5±89	32%	29%	27%	36%	30%	26%
Jul	655.3±140	23%	23%	19%	37%	31%	28%
Aug	879.6±109	33%	29%	28%	26%	23%	18%
Sep	613.7±56	25%	21%	19%	34%	32%	29%
Oct	315.5±87	58%	51%	48%	44%	42%	39%
Nov	0.0	0%	0%	0%	0%	0%	0%
Dec	0.0	0%	0%	0%	0%	0%	0%

The table above shows the total cooling energy of Case Study House 2. The table show considerable cooling energy-saving potentials for Case Study house 2 with all suggested walls. The results from

WUFI Plus and Design-Builder show the highest energy saving potentials are for wall W8LS (Limestone +Camel hair insulation +Clay Plaster 350mm) with around 33% cooling energy saving in August compared to 29% for W8MB (Mud Block +Camel hair insulation +Clay Plaster 350mm) and 28% for W2CH (Camel hair +Clay Plaster 350mm).

b) Sensible Cooling (kWh)

Table 5-36 Sensible Cooling Energy Savings (kWh) and Percentage (%)

W2CH (Camel's hair + Clay Plaster 350mm), W8LS (Limestone +Camel's hair insulation+ Clay Plaster 350mm), and W8MB (Mud Block+ Camel's hair insulation+ Clay Plaster 350mm)

Time	Benchmark (kWh)	Sensible Cooling (kWh)					
		Design-Builder			WUFI Plus		
		W8LS	W8MB	W2CH	W8LS	W8MB	W2CH
Jan	0.0	0.0	0.0	0%			
Feb	0.0	0.0	0.0	0%			
Mar	0.0	0.0	0.0	0%			
Apr	0.0	0.0	0.0	0%			
May	311.9	33%	27%	22%			
Jun	548.4	20%	16%	16%			
Jul	585.5	24%	21%	19%			
Aug	681.6	20%	15%	13%			
Sep	662.8	19%	16%	16%			
Oct	293.0	73%	71%	56%			
Nov	0.0	0.0	0.0	0%			
Dec	0.0	0.0	0.0	0%			

Table 5-38 shows the sensible cooling energy for Case Study House 2. The Table shows the potential for energy savings for all walls. The highest energy-saving potential is for wall W8LS (Limestone +Camel hair insulation +Clay Plaster 350mm), as seen in the table.

c) Zone heating (kWh)

Table 5-37 Zone Heating Energy Savings (kWh) and Percentage (%)

W2CH (Camel's hair + Clay Plaster 350mm), W8LS (Limestone +Camel's hair insulation+ Clay Plaster 350mm), and W8MB (Mud Block+ Camel's hair insulation+ Clay Plaster 350mm)

Time	Benchmark (kWh)	Zone Heating (kWh)					
		Design-Builder Results			WUFI Plus Results		
		W8LS	W8MB	W2CH	W8LS	W8MB	W2CH
Jan	698.4±120	32%	29%	25%	27%	22%	20%
Feb	640.4±11	28%	22%	22%	36%	32%	24%
Mar	502.8±57	37%	34%	31%	37%	32%	28%
Apr	406.6±42	55%	50%	48%	43%	34%	33%
May	0.0	0%	0%	0%	0%	0%	0%
Jun	0.0	0%	0%	0%	0%	0%	0%
Jul	0.0	0%	0%	0%	0%	0%	0%
Aug	0.0	0%	0%	0%	0%	0%	0%
Sep	0.0	0%	0%	0%	0%	0%	0%
Oct	0.0	0%	0%	0%	0%	0%	0%
Nov	50.2±1	24%	23%	23%	0%	0%	0%
Dec	638.5±95	19%	15%	17%	36%	31%	30%

Table 5-39 above shows the simulation results of zone heating energy from Design-Builder and WUFI Plus. The table shows the potential for energy saving with all walls. The simulation results from Design-Builder and WUFI Plus showed that the highest potential heating energy saving is for wall W8LS (Limestone +Camel hair insulation +Clay Plaster 350mm), with up to 75% In Design-Builder results for April and up to 43% in WUFI Plus results for the same month.

5.2.6 Chapter Summary

This chapter presented the results of the hygrothermal simulation of three calibrated Case Studies in Design-Builder and WUFI Plus. The results of the hygrothermal testing of materials (Capter.4) were used as a database for both software to study the impact of changing wall material on the hygrothermal comfort and any potential energy saving for the Case Study Houses. The temperature, relative humidity and energy consumption of the three Case Study models were calibrated to an acceptable limit using the calibration methodology from chapter 3 (see 3.6.1). Six different wall materials and eight different wall configurations were tested for their impact on the hygrothermal conditions of each of the Case Study Houses.

The main observations from this chapter are;

- The heat balance report of the three Case Studies showed that in addition to walls, there are heat gains and losses through the roofs, floors, and windows of the three Case Studies. To fully understand the hygrothermal performance of the tested materials and wall configurations, the Test Cell Model's roof, windows, and floor needed to be optimized (see 5.2.2). The Test Cell Model (with optimized roofs, windows and floor) was used to perform a sensitivity analysis to see the impact of material choice and wall design on the hygrothermal performance of the Test Cell Model (see 5.2.3).
- In terms of material, the sensitivity analysis revealed that Camel's Hair, followed by Limestone and Mud Block, had the highest impact on the indoor hygrothermal conditions of the benchmark model. In terms of wall configuration, W2CH (Camel's Hair + Clay Plaster 350mm), W8 (Material + Camels Hair insulation + Clay Plaster 350mm), followed by W7 (Material+ Camels Hair insulation +Cement Plaster 350mm), had the highest impact on the indoor hygrothermal conditions of the Benchmark model. Hence, walls W2CH (Camel hair +Clay Plaster 350mm), W8LS (Limestone +Camel hair insulation +Clay Plaster 350mm) and W8LS (Mud Block +Camel hair insulation +Clay Plaster 350mm) were chosen for the simulation.
- Before running the hygrothermal simulations, the selected walls, W2CH (Camel hair +Clay Plaster 350mm), W8LS (Limestone +Camel hair insulation +Clay Plaster 350mm) and W8LS (Mud Block +Camel hair insulation +Clay Plaster 350mm) were tested for their hygrothermal behaviour in

WUFI 2D under representative weather conditions. The results showed that the selected walls have passed the hygrothermal performance criteria and are suitable for use in the Libyan climate.

- The impact of changing the wall assembly on the hygrothermal comfort of the Case Study Houses was analysed based on PMV and PPD thermal comfort indicators. The results showed that the proposed walls were able to reduce indoor air temperature during summer. The results also showed that the proposed walls could (in most cases) improve the thermal sensation and reduce the occupant's thermal dissatisfaction.
- The results showed that wall W8LS (Mud Block +Camel hair insulation +Clay Plaster 350mm) had (in most cases) the highest positive impact on the hygrothermal comfort of the Case Study Houses.
- The results also showed potential heating, cooling and dehumidification energy savings for Case Study House-1 and 2 when using W2CH (Camel hair +Clay Plaster 350mm), W8LS (Limestone +Camel hair insulation +Clay Plaster 350mm) and W8LS (Mud Block +Camel hair insulation +Clay Plaster 350mm). The highest energy potential for the three Case Study Houses is when using wall W8LS.
- Finally, as the simulations were performed in two different simulation tools (Design-Builder and WUFI Plus), the overall results showed an agreement (in most cases) between the results from both software. A slight difference in the amounts of energy saving and the amount of temperature and relative humidity change was noted by comparing the results from Design-Builder and WUFI Plus. The result difference was more noticeable for Case Study House 1 and 2, compared to Case Study House 3 (Free-running). This might be because of the influence of different heating the cooling devices used in Case Studies 1 and 2.

Chapter 6, Results Discussion

6 Results Discussion

A "good" building design aims to achieve a good indoor environment, including thermal comfort, indoor air quality, acoustic comfort, and visual comfort, while delivering low energy demand and low fabric deterioration [172]. Representing the boundary between internal and external conditions, the building envelope design is a crucial factor affecting the building's energy performance and human hygrothermal comfort [173]. The materials used in the building envelope impact buildings' hygrothermal comfort and energy consumption by transferring, storing and releasing heat and moisture when the humidity and temperature conditions vary [174].

Traditional building designs often used materials and techniques in a way that enabled them to control both the indoor temperature and indoor relative humidity [94]. This allowed for a comfortable indoor environment without relying heavily on mechanical systems. In contrast, more recent building designs and materials can provide poorer thermal and hygrothermal performance, resulting in more significant discomfort and increased energy demands [175]. This can be due to the use of less-effective materials or less-optimized envelope designs.

In regions such as Libya, where the climate is hot and dry with high temperature variations and low relative humidity, the hygrothermal performance of building envelopes is especially critical. Furthermore, traditional materials and building techniques in Libya are facing the challenge of being replaced by modern building materials and techniques that are often imported and not optimized for the local environment.

This thesis aims to investigate how traditional and modern building materials might be used to improve hygrothermal comfort in Libyan domestic buildings. This was achieved through Hygrothermal and energy performance monitoring of three Case Studies, hygrothermal categorization of common traditional and modern building materials via laboratory experiments, and through hygrothermal simulation and energy simulations of Case Studies using Design-Builder and WUFI Plus. By examining the performance of various materials and systems, this research aims to provide guidance on how to optimize the use of materials and envelope systems to create a more comfortable and energy-efficient domestic buildings in Libya.

- ***Literature review (chapter 2)***

At the outset of this research project, the primary goal was to investigate the impact of envelope materials and design on the hygrothermal comfort and energy consumption of Libyan houses. To achieve this, a comprehensive survey was initially planned to cover the occupants' hygrothermal comfort, behaviour, and responses to varying thermal conditions, as well as an energy use survey.

However, due to practical constraints and time limitations, some of these aspects were only completed through modelling, and were therefore not discussed in detail in the literature review chapter. Nonetheless, the preliminary results of these surveys can be found in the Appendices.

The building envelope, as the boundary between the indoor and outdoor environments, is critical to controlling indoor hygrothermal conditions. Chapter 2 of this study focuses on the use of building envelopes to achieve this control. Through a literature review, various factors that directly influence occupant hygrothermal comfort and climate factors that impact indoor hygrothermal conditions were identified. The review also revealed that the hygrothermal behaviour of the envelope is governed by the material's functional properties, including Density (ρ), Thermal Conductivity (λ), Specific Heat Capacity (C_p), Porosity (ϕ), Water Absorption Coefficient (Aw), and Water Vapor Diffusion Resistance Factor (μ Value).

The findings presented in chapter 2 underscore the critical role of materials with hygrothermal properties in managing indoor hygrothermal conditions, which can lead to reduced energy consumption and improved indoor air quality, with consequential benefits for both human health and the environment.

While the literature review conducted in chapter 2 did provide valuable data on the hygrothermal properties of construction materials from various sources, including published research and online material databases, it also highlighted some notable limitations. For instance, the variability in the values of hygrothermal properties reported in published studies (as shown in Table 2-5) may reflect differences in the materials across geographical locations or variations in composition due to the presence of fillers or additives. This raises questions about the comparability of data obtained from different studies and regions, and the suitability of relying on published studies alone for determining the hygrothermal properties of materials.

Furthermore, the absence of published data on the hygrothermal properties of Libyan construction materials is a significant limitation that constrains the ability of architects and engineers in the region to design energy-efficient, comfortable, and healthy buildings. The laboratory-based experiments conducted in Chapter 4 to address this gap in knowledge are a crucial contribution to the field, but they also underscore the need for more research on the hygrothermal properties of construction materials in various regions and under different conditions.

Overall, the research presented in chapters 2 and 4 highlights the importance of careful material selection in building design, particularly in regions with extreme environmental conditions. It also emphasizes the need for more comprehensive and reliable databases of hygrothermal properties that can help inform building design decisions. By addressing these issues, architects and engineers in Libya can design buildings that are not only sustainable and energy-efficient but also comfortable and healthy for occupants, contributing to mitigating the effects of climate change (see section 3.4).

Chapter 2 of this study provides an overview of the importance of thermal comfort and its measurement in building design. As national standards for measuring thermal comfort are absent in Libya, this research relied on Fanger's Predicted Percentage of Dissatisfied (PPD) and Predicted Mean Vote (PMV) thermal comfort indices. These indices have been widely used in countries with similar climates and cultures, as supported by the literature review. In this research, the PMV and PPD indices were used to assess the impact of wall design and material selection on the hygrothermal conditions of the Case Study Houses, as discussed in Chapter 5.

Moreover, Chapter 2 conducted a review of various protocols and methodologies for building model calibration and simulations. The literature review highlighted a performance gap between simulation results and actual measured energy use in operational buildings, indicating the need for more accurate calibration of building models. To address this issue, a five-step simplified calibration methodology was adopted for this research based on the review of academic publications and calibration guidelines. The three Case Study Houses were successfully calibrated to a satisfactory accuracy level using measured annual weather and energy consumption data, adhering to international guidelines from ASHRAE, EVO, and FEMP.

The findings of Chapter 2 indicate that building envelope materials and design can significantly affect indoor hygrothermal comfort and energy consumption in Libyan domestic buildings. The research methodology adopted in this study provides a comprehensive approach for evaluating and optimizing building envelope design and material selection for hygrothermal comfort and energy efficiency for Libyan domestic buildings. By addressing the issue of calibration, this research provides a more accurate evaluation of building performance, thus improving building design and energy efficiency.

- ***Material testing (chapter 4)***

The hygrothermal experiments in chapter 4 included testing the following properties; Moisture Buffer Value ((MBV), (g/m^2 RH%)), Water Vapor Diffusion Resistance Factor ((μ Value), (-)), Sorption Isotherm ((u), (Kg/Kg)), Water Absorption Coefficient ((Aw), ($Kg/(m^2\sqrt{t})$)), Density ((ρ), (Kg/m^3)), Thermal Conductivity ((λ), (W/m. K)), Thermal Diffusivity ((α), (m^2/s)), Specific Heat Capacity ((C_p), (KJ/kg. K)). The Porosity test was not undertaken due to Covid-19.

Due to the Covid-19 pandemic, laboratory facilities were closed, and we were unable to conduct the planned experiments to measure the properties of the materials samples. To overcome this challenge, we designed a simple experiment setup using saturated salt solutions and basic equipment, as described in detail in Chapter 3 of this thesis. However, it was not possible to measure the porosity of the materials samples using the available equipment. Therefore, we obtained the porosity value from published material data, which is cited in Table 2.5 and Table 2.6.

While the simple experiment setup provided an alternative method to measure the properties of the materials samples, we acknowledge that the results obtained using this approach may not be as precise as those obtained in a full laboratory setting. Nonetheless, we believe that our findings still contribute valuable insights to the field.

The main findings of chapter 4 showed that some of the building materials from Libya are unique to the country's climate and geographic context and can vary from the results of other researchers from different geo-climatic contexts. These findings highlight the importance of conducting experimental laboratory investigations and testing material focusing on different geographical areas.

In terms of Moisture Buffering Value (MBV), the results showed that only Mud Blocks had an "excellent" MBV. The MBV test results for Mud Blocks align with the values found in the published research (see Table 2-5). The lowest MBV was observed for Hollow Concrete samples (Table 4-1). The finding of the MBV test showed that Mud blocks, followed by Limestone, have the highest moisture buffering capacity compared to the remaining materials.

In terms of Aw value, both Mud block and Clay samples showed low resistance to water absorption (see section 4.2.4.3.), meaning that these two materials might require some protection to withstand the harsh outdoor environment.

In terms of Aw value, the findings in Section 4.2.4.3 indicate that both Mud block and Clay samples exhibit low resistance to water absorption, suggesting that these materials may be vulnerable to damage from the harsh outdoor environment. To prevent moisture from penetrating the Clay/Mud wall and compromising its structural integrity, various protective measures can be employed.

One option is to apply a waterproof coating or sealant to create a barrier against water and moisture. Another approach is to use lime plaster or render, which can protect the external wall from the elements while allowing the wall to "breathe" and regulate moisture levels. A rainscreen system, which creates a cavity between the wall and the cladding, can also help to prevent moisture accumulation and promote air circulation.

It is worth noting, however, that these protective techniques may affect the performance of the wall and materials, and thus should be carefully evaluated in future research. It may be necessary to consider the trade-offs between protective measures and their potential impact on the wall's aesthetics, durability, and energy efficiency.

In summary, the Aw test results highlights the need for protective measures to safeguard the structural integrity of Clay/Mud walls in harsh outdoor environments. The use of waterproof coatings, lime plaster, render, or rainscreen systems may help to mitigate the effects of moisture and promote the long-term sustainability of these materials. However, further research is needed to fully evaluate the effectiveness and potential drawbacks of these protective measures.

The highest Aw value is recorded for Limestone. In contrast, the lowest Aw value is noted for the Hollow Concrete Samples compared to the other materials (see Figure 4-17).

Sorption isotherm analysis revealed that all materials exhibited different types of isotherms, indicating that each material has a unique capacity for moisture absorption and release. Our results showed that Camel's Hair samples exhibited the highest hygroscopicity in terms of average moisture content mass by mass (MCw). Meanwhile, Clay samples had the highest capacity for moisture absorption in terms of average moisture content mass by volume (MCv). Finally, all materials were capable of releasing all absorbed moisture back into the air, with Hollow Concrete and Sandstone demonstrating the fastest and slowest response rates, respectively, compared to the other materials.

Thermal properties were measured using a transient technique method with an ISOMET 2114 Thermal Properties Analyser (see Table 2-3). The obtained Thermal Conductivity, Thermal Diffusivity, and Volumetric Heat Capacity were used to derive the Specific Heat Capacity (see 3.5.1.6.1.). Our results showed that the measured values were generally within the range of published data for the tested materials, although some variation was observed (see Tabel 4-11).

In terms of thermal analysis, Limestone exhibited lower Thermal Conductivity and higher Specific Heat Capacity than the other materials tested, suggesting that it has greater thermal mass and resistance. Mud blocks exhibited low Thermal Conductivity and relatively high Specific Heat Capacity, indicating that they have greater thermal mass and resistance compared to Hollow Concrete and Sandstone samples. Similarly, Clay exhibited relatively low thermal conductivity and specific heat capacity, similar to that of Limestone samples. Camel's Hair, intended for use as an insulating material, exhibited the lowest density and thermal conductivity, while its specific heat capacity was the highest among the materials analysed.

Furthermore, the main findings from chapter 4 can be summarised as follow;

- Only Mud Blocks had an "excellent" Moisture Buffering Value (MBV), while the lowest MBV was observed for Hollow Concrete samples.

- Both Mud block and Clay samples exhibited low resistance to water absorption, meaning that these two materials might require some protection to withstand the harsh outdoor environment.
- The Sorption Isotherm analysis revealed that all materials exhibited different types of isotherms, indicating that each material has a unique capacity for moisture absorption and release.
- Limestone exhibited lower Thermal Conductivity and higher Specific Heat Capacity than the other materials tested, suggesting that it has greater thermal mass and resistance.
- Mud blocks exhibited low Thermal Conductivity and relatively high Specific Heat Capacity, indicating that they have greater thermal mass and resistance compared to Hollow Concrete and Sandstone samples.
- Camel's Hair, intended for use as an insulating material, exhibited the lowest density and thermal conductivity, while its specific heat capacity was the highest compared to the rest of the material samples.

Based on our testing, Limestone, Mud block, Camel's Hair, and Clay showed the most promise for moisture buffering and control of surface radiant temperature and relative humidity. Consequently, we used these materials to construct various wall combinations, which were later tested for their hygrothermal behaviour in WUFI 2D (see 3.6.6 and 5.2.4). These results will help inform the design of energy-efficient and sustainable buildings that can maintain comfortable and healthy indoor environments.

- ***Calibration and simulation of building models (chapter 5)***

In this study, the hygrothermal and energy performance of three Case Studies were monitored for 12 months at sub-hourly intervals (see Section 3.3.). The data from the monitoring was used to create computer models for the three Case Studies in Design-Builder and WUFI Plus (see section 3.5.1.). By applying the adopted methodology from published research (see Table 2-7), the Case Study Models were calibrated to the accuracy criteria set by ASHRAE, EVO, and FEMP (see Table 2-6). The calibration of the Case Study models was a time-consuming process; however, it was noticed that increasing the amount of data collection can help reduce the calibration time significantly. It was also found that having representative actual weather data is key to improving the accuracy of calibration results.

In section 5.2., The calibrated models were used to investigate the impact of changing wall materials (using the results from chapter 4) on the hygrothermal comfort of the Case Study Houses. The methodology for the hygrothermal simulation is listed in section 3.5.1.

Two sensitivity analysis were performed in chapter 5, the first sensitivity analysis was performed to assess which of the building material (Limestone, Hollow Concrete, Sandstone, Mud Block, Clay and Camel's Hiar) had the highest impact on the hygrothermal condition of the Test Cell Model. The second sensitivity analysis was performed in order to understand which of the wall configuration (W1-W8, see Table 3-17), had the highest impact on the indoor hygrothermal conditions.

The sensitivity analysis results showed that all the proposed walls helped reduce the indoor temperature of the Case Study benchmark in ranges of 0.5-1C^{o}. The sensitivity analysis also showed that walls W2CH (Camel's hair+ Clay Plaster 350mm), W8LS (Limestone +Camel hair insulation +Clay Plaster 350mm) and W8LS (Mud Block +Camel hair insulation +Clay Plaster 350mm) had the highest impact on the indoor temperature and the relative humidity of the Test Cell Model. This is expected since chapter 4 showed that Camels' hair, Limestone, Clay and Mud blocks have relatively good hygrothermal properties compared to the Sandstone and Hollow Concrete.

The hygrothermal behaviour of the selected walls from the sensitivity analysis was simulated using WUFI 2D, in order to evaluated the hygrothermal behaviour of the selected walls over time, and to detect any moisture related issues, such as condensation, mould growth, dryness rate, and to make sure that the selected walls (W2CH (Camel hair +Clay Plaster 350mm), W8LS (Limestone +Camel hair insulation +Clay Plaster 350mm) and W8LS (Mud Block +Camel hair insulation +Clay Plaster 350mm)), meets the AHRAE 160 160 criteria for moisture control design analysis in buildings.

- Total Moisture Content (TMC).
- Dryness Rate (DR).
- Condensation Risk (CR).
- Mould Growth
- ASHRAE-160 Criteria.

The first hygrothermal behaviour criteria was the total moisture content. This criteria measure the ability of wall assembly to dry out over time. The three selected walls W2CH W8LS and W8LS, were able to pass this criteria and showed an ability to dry out overtime and therefore, the three walls have passed this criteria.

The second evaluation criteria was the dryness rate. This criteria measures the rate at which the wall will dry overtime. The results showed that all walls have a positive and relatively high DR rate. The figure also showed that the highest DR Rate is for wall W8MB followed by W2CH and W8LS. The results confirmed that all walls have passed this criteria.

The condensation risk was also calculated for the selected walls. The results showed that in the three walls (W2CH W8LS and W8LS), the likelihood of condensation is minimum and hence, the three walls have passed this condensation risk criteria.

Mould growth probability was also evaluated as part of the hygrothermal behaviour evaluation criteria. The results showed that the three walls have a minimum risk of mould growth and the therefore, the three wall have passed the mould growth criteria and are safe from mould growth under the Libyan climate conditions.

Finally, the hygrothermal behaviour of the three walls was compared against the ASHRAE 160 criteria for moisture control design analysis in buildings. The results from WUFI 2D confirmed that the three walls have achieved the ASHREA 160 criteria and hence, are suitable for use in the Libyan climate.

The selected walls from the hygrothermal behaviour criteria will be used to assess the impact of changing wall design and material on the hygrothermal comfort of the Case Study Houses.

The hygrothermal comfort of the Case Study House was assessed using Fagner's PMV-PPD% thermal comfort indicates. The results showed that the thermal sensation of the occupants of the Case Study Houses was improved in most cases when using the wall W2CH (Camel hair +Clay Plaster 350mm), W8LS (Limestone +Camel hair insulation +Clay Plaster 350mm) and W8LS (Mud Block +Camel hair insulation +Clay Plaster 350mm). Walls W8LS, W8MB and W2CH also showed a noticeable heating, cooling, and dehumidification energy savings for Case Study Houses 1 and 2. Wall W8LS (Limestone +Camel hair insulation +Clay Plaster 350mm), had the highest positive impact on the hygrothermal comfort and energy performance of the Case Study Houses.

Finally, it was noted from the results that both Design-Builder and WUFI Plus produced similar but slightly different value results.

To conclude this discussion, it is worth mentioning that the material included in this thesis are the row materials of Libya. In this research, the impact of those material on the hygrothermal comfort of Libyan houses was tested in modelling. In practice however, there will be some issues to deal with final finishes, decorations, protection form elements (rain for example), and physical damage. These issues will be dealt with in future work, and the impact of these factors will be assessed further.

Chapter 7, Conclusion

7 Conclusion

At the outset of this research, the intention was to conduct surveys of occupants' thermal comfort, energy use, and behaviour. However, due to time constraints and the outbreak of COVID-19, these surveys were not completed. The initial results of the survey, along with the ethical approval application for monitoring the Case Study Houses and conducting the survey, can be found in the Appendices.

Despite these limitations, this study has made significant and valuable contributions to the field of hygrothermal performance of building materials, their impact on energy efficiency, and occupant comfort in Libyan domestic buildings. Specifically, this study has developed a novel construction material database for Libya, which fills a significant gap in knowledge regarding the hygrothermal properties of Libyan building materials. This accurate and representative data can lead to improved building simulations and design strategies, ultimately enhancing occupant comfort and energy efficiency.

Furthermore, the investigation of different wall configurations and materials has revealed insights that can inform professionals and decision-makers in Libya on the selection of appropriate building materials. This information can help reduce dependence on mechanical services, lower energy consumption, and carbon emissions while ensuring occupant comfort. These findings can also have a global impact on sustainable building practices.

In conclusion, this research has paved the way for future studies exploring the impact of other building components on hygrothermal performance and the use of traditional and modern building materials in combination for optimal hygrothermal and energy performance. Thus, it contributes to the advancement of sustainable building practices.

To further disseminate the research findings, it is intended to submit the findings of this work for publication in a peer-reviewed journal within the next six months, with the hope that this research will contribute to the ongoing dialogue on sustainable building practices and inspire future research on the impact of material and wall design choices on energy use and hygrothermal comfort in domestic buildings.

The conclusions against each of the thesis objectives to achieve the thesis aims are:

- Objective 1. To measure and compare the hygrothermal properties of traditional and modern building materials used in Libya via laboratory measurements.

The hygrothermal conditions in Libyan houses can be challenging due to the hot and arid climate, which can have significant impacts on building materials and the indoor environment. By investigating the hygrothermal properties of Libyan building materials and their impact on comfort and energy use, this study can provide insights into the design and operation of buildings that are suitable for the local climate conditions. Common construction material samples representing Libya's common traditional and modern building materials were tested to determine their hygrothermal properties. The overall findings from the laboratory investigations showed that construction materials can be unique to their geographical locations and can vary from the results of other researchers from different geographical contexts. The results of chapter 4 showed good hygrothermal properties for Camel's hair, Limestone, Clay, and Mud block compared to Sandstone and Hollow Concrete, indicating these materials' ability to passively provide some degree of controlling the indoor hygrothermal conditions. The conclusions against each of the thesis objectives suggest that the findings of this research can potentially contribute to the development of better building codes and standards, as well as the design of more sustainable and comfortable buildings in the region.

- *Objective 2. Use the outputs of objective one to assess new wall constructions which combine traditional and modern materials and to optimise these constructions in the hygrothermal simulation software WUFI Plus.*

Based on current Libyan framed construction techniques, 128 different potential wall material combinations were proposed and tested to establish their overall properties for use within Objective 3. The hygrothermal behaviour of walls W2CH (Camel hair +Clay Plaster 350mm), W8LS (Limestone +Camel hair insulation +Clay Plaster 350mm) and W8LS (Mud Block +Camel hair insulation +Clay Plaster 350mm) was assessed based on the simulation results from WUFI 2D and the hygrothermal behaviour criteria. The results showed that all walls pass the hygrothermal behaviour criteria and therefore are suitable to be used for Libya with no potential risk of condensation, mould growth or any other moisture-related issues.

- *Objective 3. To investigate the variation in hygrothermal comfort performance of three Case Study domestic buildings in Libya using various wall constructions, with reference to current wall constructions.*

Calibrated Case Study models allowed assessment of the impact of varying the wall materials on the hygrothermal performance of the Case Study Houses. The key finding is that material choice can significantly impact hygrothermal comfort, with wall W8LS (Limestone + Camel hair insulation + Clay Plaster, 350mm) having the highest positive impact on indoor hygrothermal conditions. Modelling showed it could reduce the indoor temperature of the Case Study Houses in the range of 0.5-1^{o}C. It was also found that replacing the benchmark wall with wall W8LS had the following impacts:

- It would improve hygrothermal comfort in many cases, especially during the hot months.
- The potential of up to 75% saving on cooling energy and up to 48% on Heating energy.

- A potential to save up to 38% dehumidification energy.

The three Case Study Houses simulations showed that the current common building envelope design for Libyan housing could be markedly improved. Despite two of the 3 Case Study houses having heating and cooling systems installed, which the electrical monitoring showed were being used, these buildings fared no better in terms of hygrothermal comfort performance than the unconditioned building, which was the final Case Study. This was slightly unexpected, and further occupant research is needed to understand the perceived comfort of the occupants of these buildings.

Once being published, Chapter 4's findings will provide valuable insights into the hygrothermal properties of construction materials of Libya, increasing the reader's understanding of the subject matter. This knowledge will be especially helpful for architects and engineers in Libya, as it will allow them to obtain more accurate simulation results that better reflect the specific materials, climate, and location in Libya. Additionally, the results from Chapter 5 will be useful for decision-makers and professionals in Libya to comprehend the effects of utilizing various wall configurations and materials on the hygrothermal and energy performance of Libyan houses.

Moreover, the findings of this research can be useful for professionals, architects and engineers and can inspire building design and construction leading to a more hygrothermal comfortable and energy efficient houses for Libya, by choosing the appropriate building materials that can help regulate indoor temperature and relative humidity. The findings of this research can also be used to develop moisture control strategies for houses in Libya, by applying and deploying the appropriate envelope design that can help in moisture control in houses. Although it was not considered in this research and would need to be considered in more details, the findings of this study might be used to improve the indoor air quality for Libyan houses, by avoiding building materials that are susceptible to mould growth and other forms of microbial activity and by choosing a proper ventilation system design to maintain healthy indoor air quality levels.

This study offers valuable insights into the hygrothermal properties of building materials in Libya and their potential to enhance indoor comfort in domestic buildings. Future research is warranted to investigate the feasibility of utilizing these materials in practical applications, including an assessment of their availability, quality, and the required craftsmanship. Such research could provide a foundation for the development of sustainable and efficient building solutions that improve the well-being of occupants and promote environmental sustainability.

Overall, the research that has been done in this thesis can be the starting point to practical applications that result in more comfortable, durable, and healthy buildings for Libya.

7.1 Limitations

One of the original aims of this thesis was to investigate the impact of material and wall design choices on energy use. However, due to time constraints and unexpected findings, the amount of time allocated for studying energy use was limited, resulting in an initial set of results obtained through modelling. While the collected weather, energy and occupant behaviour data is still available for future analysis and can be found in the Appendices, the focus of this study shifted to the hygrothermal properties of the material samples and how can they contribute to hygrothermal comfort in Libyan domestic buildings.

It is important to acknowledge the limitations of any research study, and this study is no exception. Although every effort was made to design a reliable experimental setup using saturated salt solutions and basic equipment, this approach may, in some cases, have introduced potential sources of error. For example, the precision of the measurements may have been slightly lower than what could be achieved in a full laboratory setting.

Despite these limitations, the findings still provide valuable insights into the properties of the material samples. By using this alternative approach, data was collected during a time when laboratory facilities were not available due to the Covid-19 pandemic.

To ensure the integrity of the study, several measures were taken to minimize sources of error, such as controlling for temperature and humidity and carefully calibrating the equipment. Multiple trials were also conducted and the data was analysed thoroughly to account for any variability in the results.

Overall, while this study has some limitations, the findings contribute to the field and provide a valuable starting point for future research. By being transparent about the limitations of the study, it is hoped to encourage further discussion and investigation into the properties of these material samples.

Another significant finding of this research is the development of a novel construction material database for Libya. Once this database is published, it will assist architects and engineers in obtaining more accurate simulation results that represent the Libyan material, climate, and location, using actual weather data.

However, there are several limitations to this research that should be noted. Firstly, due to safety and security reasons, it was impossible to monitor traditional buildings during this research. Therefore, the monitoring of case studies was limited to three representative modern domestic buildings. Additionally, this research only investigated wall materials and did not include testing and optimizing other elements, such as roofs, floors, and windows. Finally, due to limited access to resources because of Covid-19, it was not possible to experimentally investigate the porosity of the construction materials.

Furthermore, it is important to note that this study only investigates the hygrothermal properties of building materials through experiments and does not consider other factors such as the availability of resources, craftsmanship, and applicability of the materials in the real-world context.

7.2 Future work

With reference to the results obtained from this research, suggestions for future work are presented here:

- The Porosity of the material samples should be experimentally investigated.
- Further research investigating the impact of changing the envelope materials on the hygrothermal comfort of public buildings, such as educational or commercial buildings, will be appealing.
- The hygrothermal properties were only investigated at the material level. The hygrothermal performance of the materials at an assembly or system level should be investigated in laboratory experiments or in-service conditions.
- Studying the impact of changing the roof's material and testing for different materials for roofs (using Camel's hair, for example) and research for optimized windows for Libya should be considered.
- Testing and optimizing locally available resources for insulation materials, for instance, palm trees, olive tree leaves, or a mixture of both, should be considered.
- Research on the impact of internal and external wall plaster on the hygrothermal comfort of Libyan buildings and optimizing new wall coating and plastering materials mixing Camel's hair with Clay or Mud would be interesting.

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Appendices

A1- Operation and Occupancy Schedules in Design-Builder and WUFI Plus

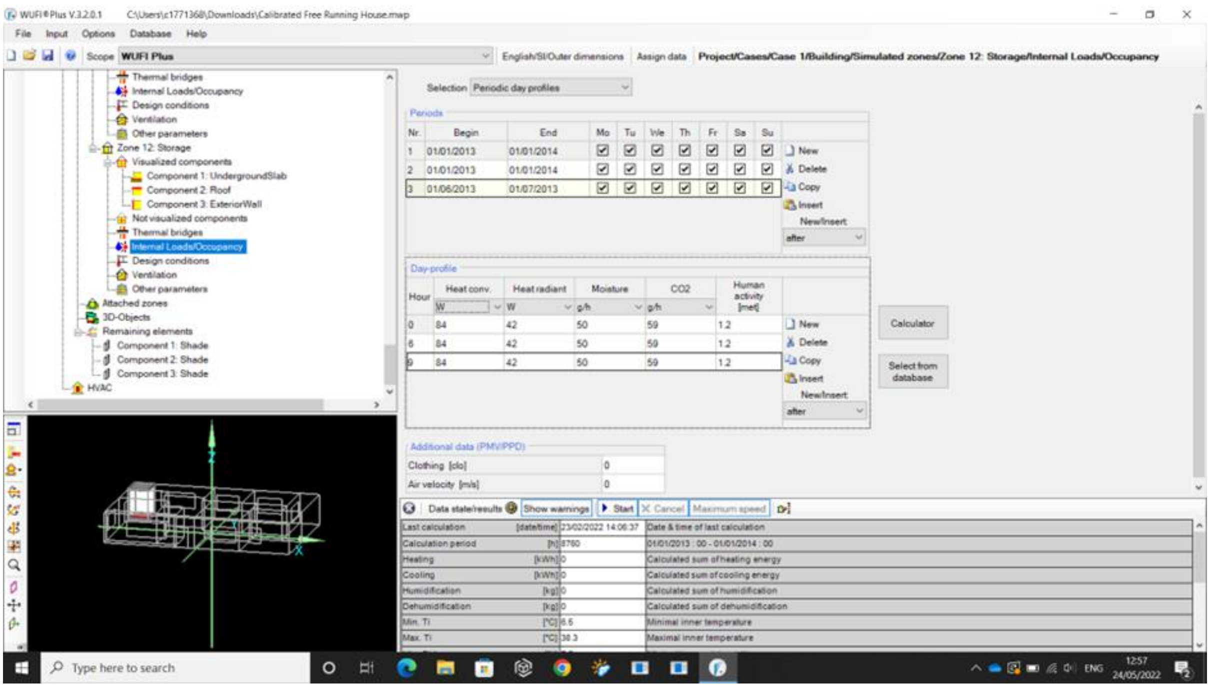


Figure A1-1 Operation and Occupancy Schedule (WUFI Plus, Jun-Jul)

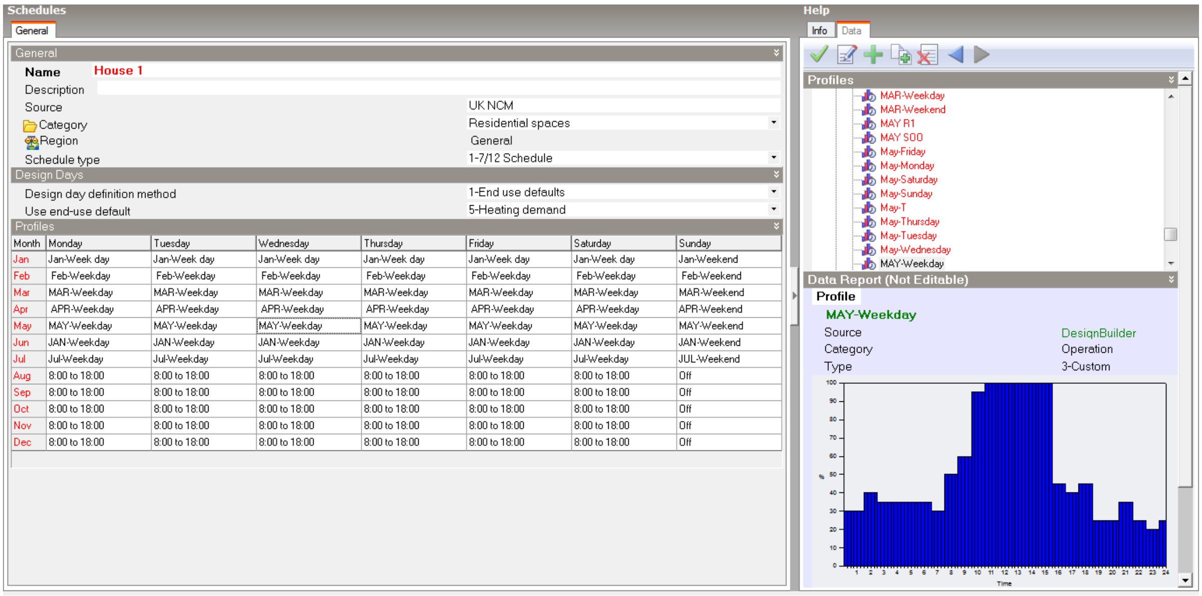
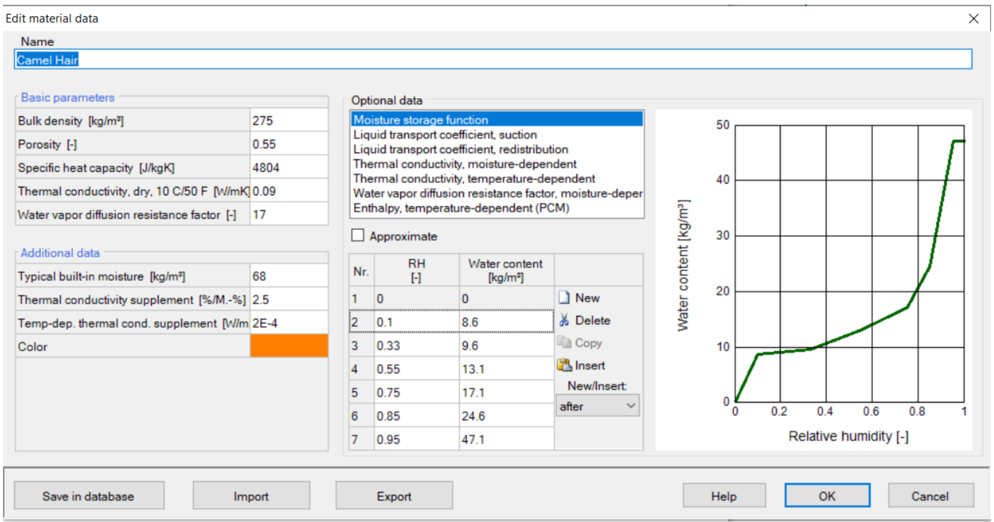
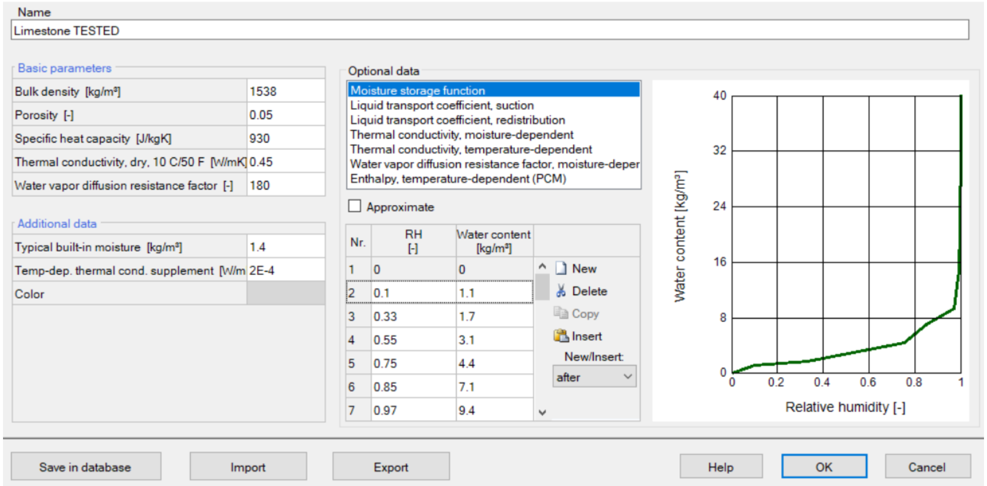


Figure A1-2 Operation and Occupancy Schedule (Design-Builder, Jun-Jul)

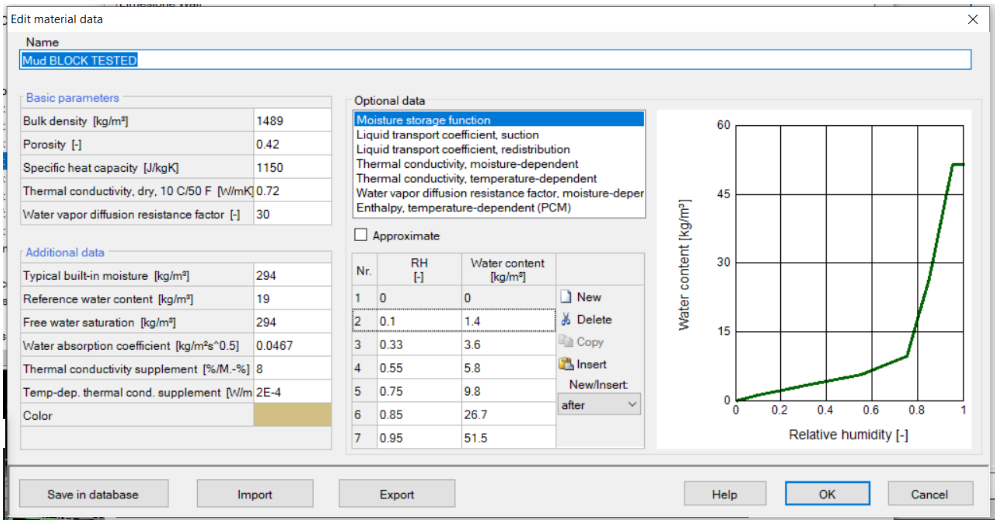
A2- WUFI Plus/WUFI 2D Material Data Sheet



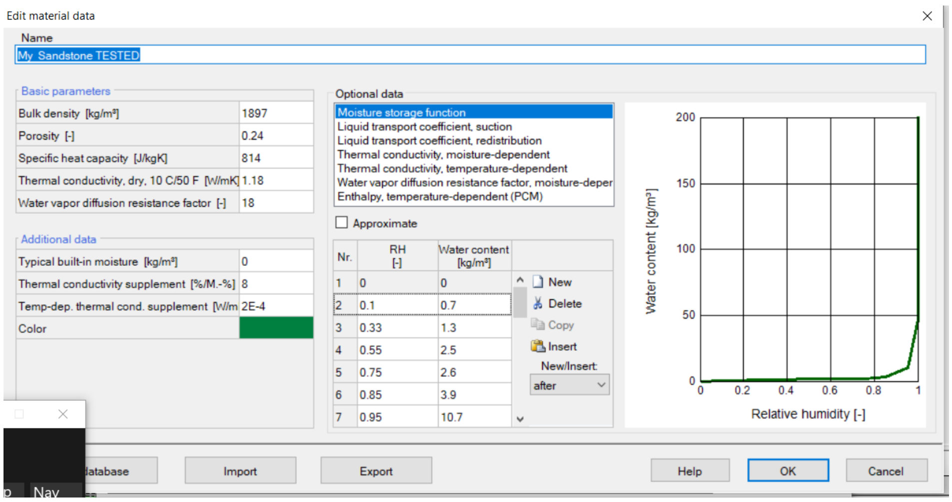
A2-1 WUFI Plus/WUFI 2D Material Data for Camel's hair



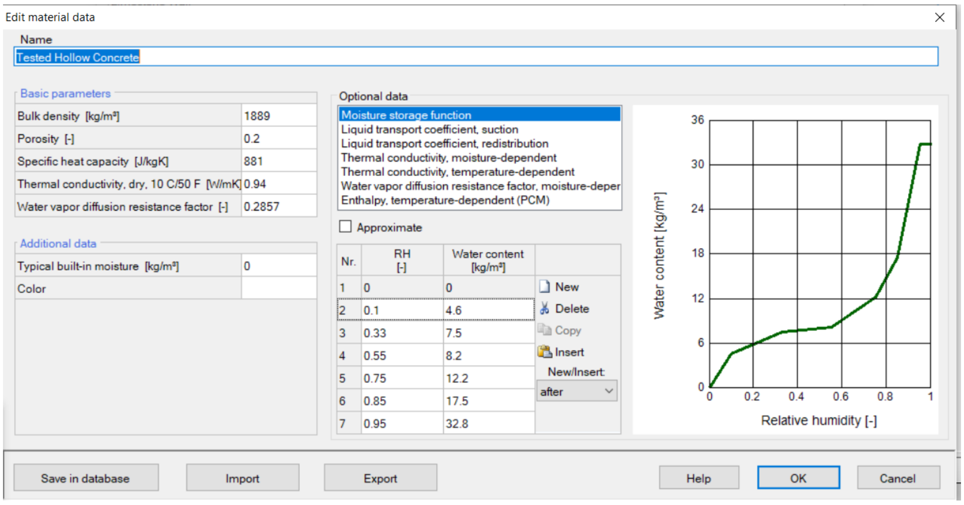
A2-2 WUFI Plus/WUFI 2D Material Data for Limestone



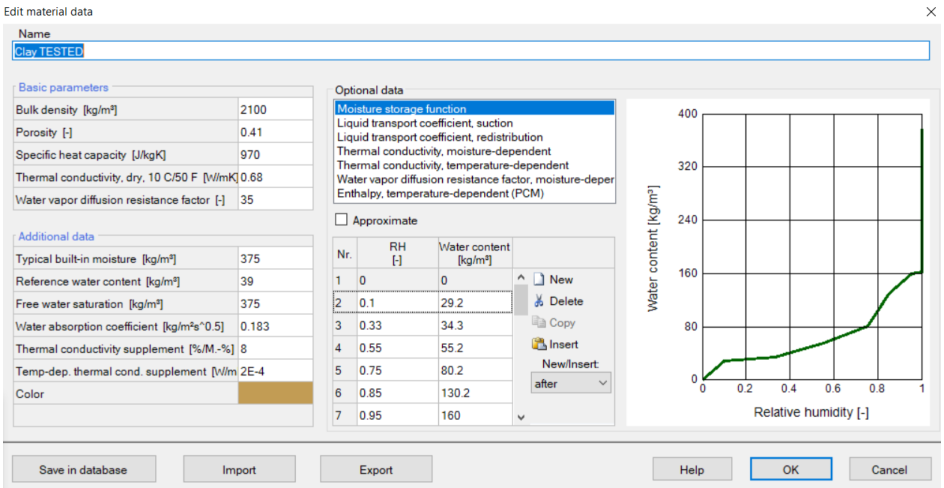
A2-3 WUFI Plus/WUFI 2D Material Data for Mud Block



A2-4 WUFI Plus/WUFI 2D Material Data for Sandstone

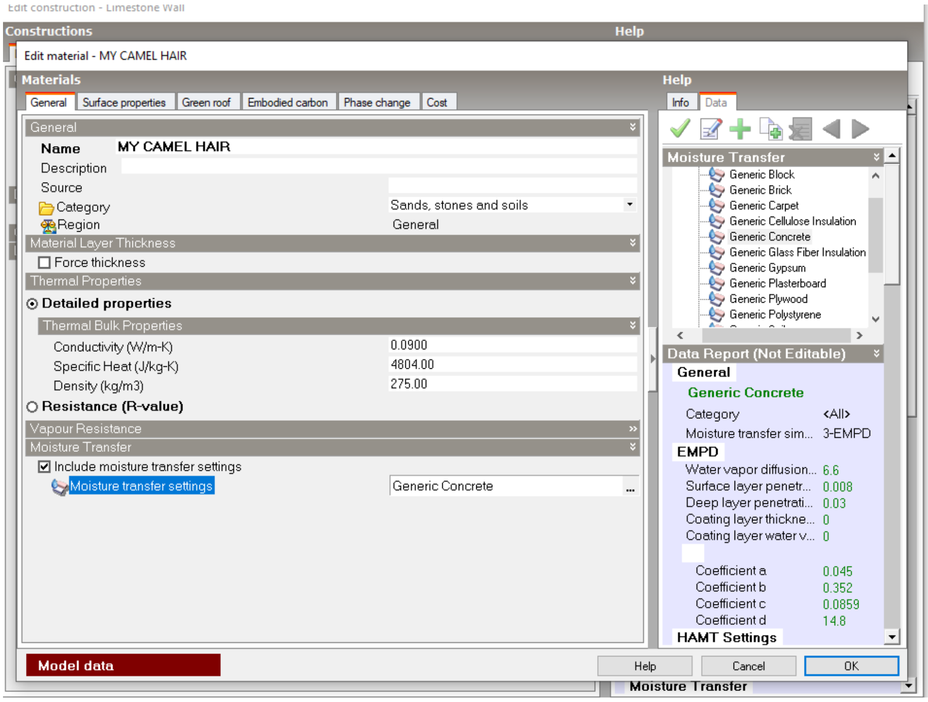


A2-5 WUFI Plus/WUFI 2D Material Data for Hollow Concrete

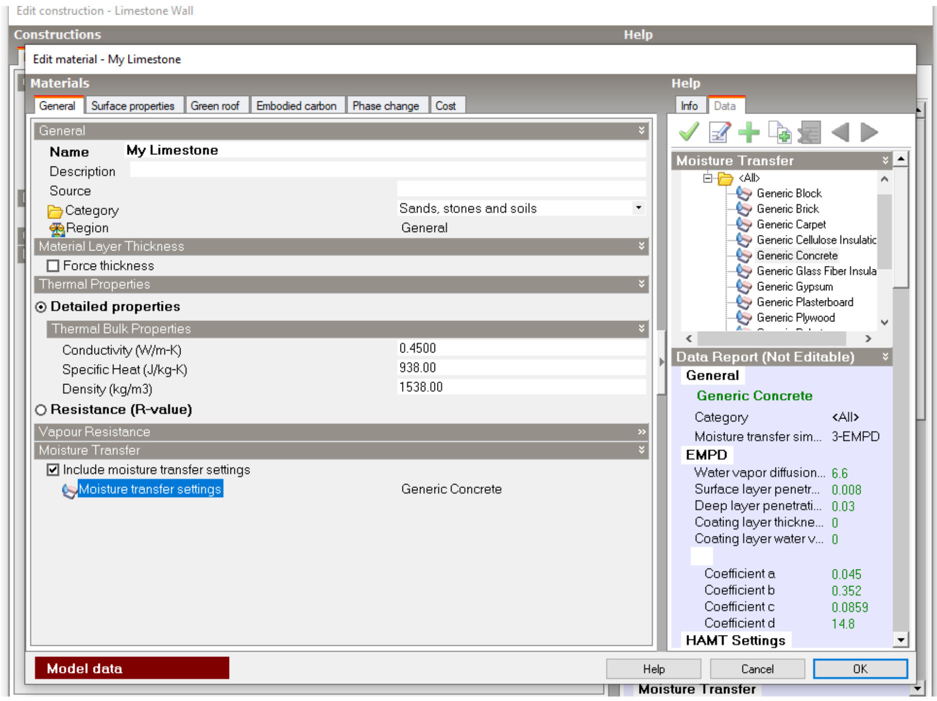


A2-6 WUFI Plus/WUFI 2D Material Data for Clay

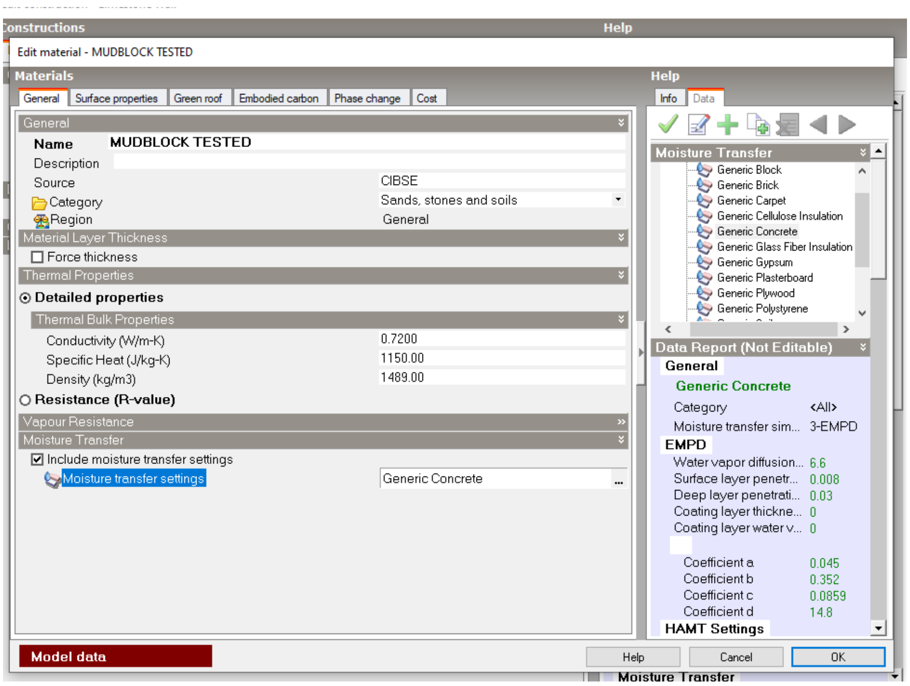
A3- Design-Builder Material Data Sheet



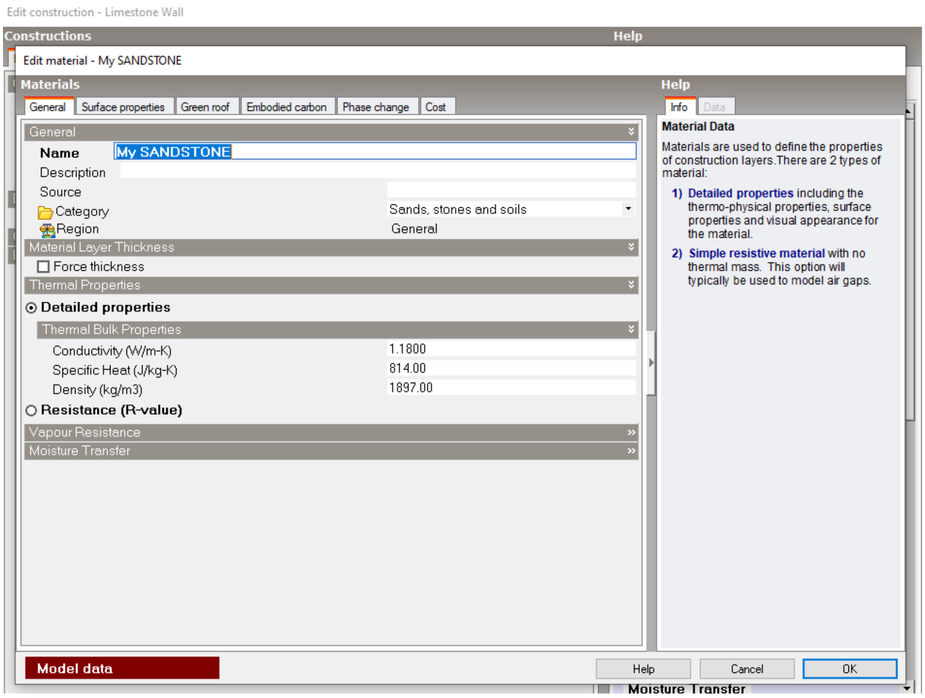
A3-1 Design-Builder Material Data for Camel's hair



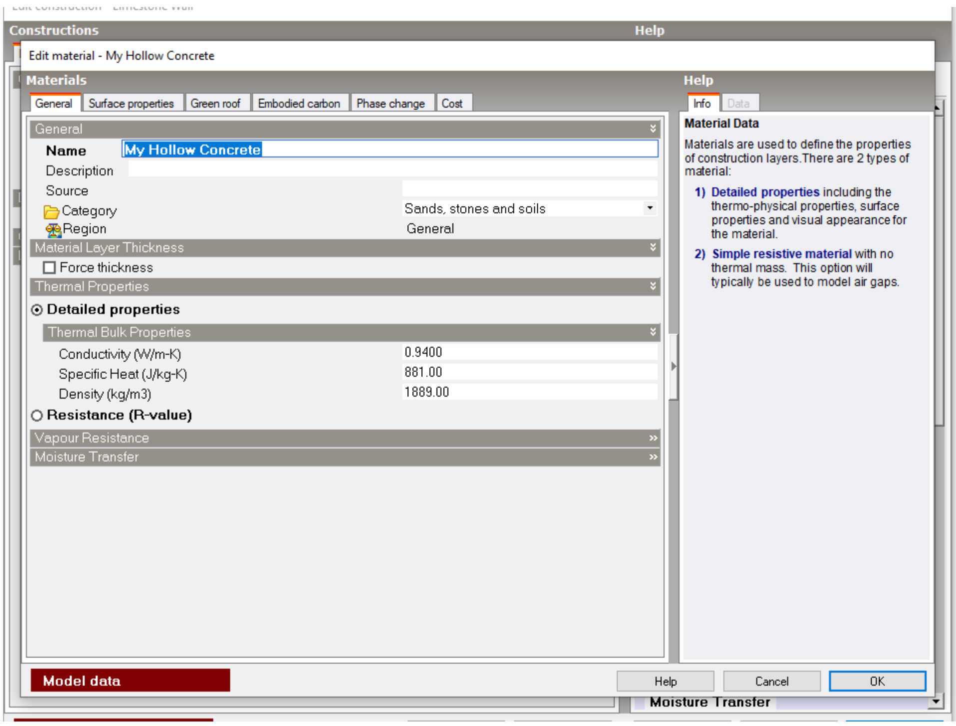
A3-2 Design-Builder Material Data for Limestone



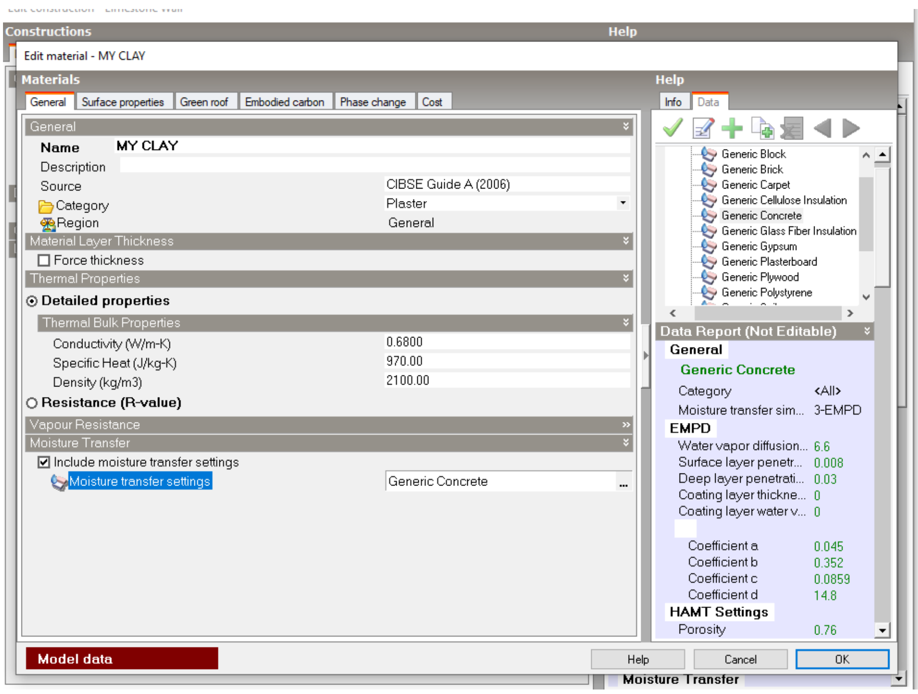
A3-3 Design-Builder Material Data for Mud Block



A3-4 Design-Builder Material Data for Sandstone



A3-5 Design-Builder Material Data for Hollow Concrete



A3-6 Design-Builder Material Data for Clay

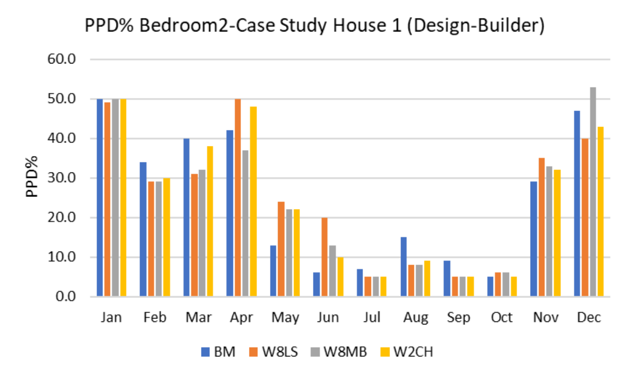
A4- PMV-PPD Results for the Case Studies

Case Study House 1

a) Bedroom-2 (Design-Builder Results)

Table A4-1 PMV-Bedroom-2-Case Study House-1 (WUFI Plus)

Time	Benchmark		W8-LS		W8-MB		W2CH	
	PMV	Sensation	PMV	Sensation	PMV	Sensation	PMV	Sensation
Jan	-1.6	Cool	-1.5	S-Cool	-1.5	Cool	-1.5	S-Cool
Feb	-1.2	S-Cool	-1.1	S-Cool	-1.1	S-Cool	-1.1	S-Cool
Mar	-1.3	S-Cool	-1.1	S-Cool	-1.3	S-Cool	-1.3	S-Cool
Apr	-1.3	S-Cool	-1.5	S-Cool	-1.2	S-Cool	-1.5	S-Cool
May	-0.6	S-Cool	-1.0	S-Cool	-0.9	S-Cool	-0.9	S-Cool
Jun	0.0	Neutral	-0.8	S-Cool	-0.6	S-Cool	-0.5	S-Cool
Jul	0.0	Neutral	0.0	Neutral	0.0	Neutral	0.0	Neutral
Aug	0.7	S-Warm	0.0	Neutral	0.0	Neutral	0.0	Neutral
Sep	0.0	Neutral	0.0	Neutral	0.0	Neutral	0.0	Neutral
Oct	0.0	Neutral	0.0	Neutral	0.0	Neutral	0.0	Neutral
Nov	-1.1	S-Cool	-1.2	S-Cool	-1.2	S-Cool	-1.1	S-Cool
Dec	-1.4	S-Cool	-1.3	S-Cool	-1.5	Cool	-1.4	Cool



Time	BM	W8LS	W8MB	W2CH
Jan	50.0	**49.0**	50.0	50.0
Feb	34.0	**29.0**	**29.0**	**30.0**
Mar	40.0	**31.0**	**32.0**	**38.0**
Apr	42.0	**50.0**	**37.0**	**48.0**
May	13.0	**24.0**	**22.0**	**22.0**
Jun	6.0	**20.0**	**13.0**	**10.0**
Jul	7.0	**5.0**	**5.0**	**5.0**
Aug	15.0	**8.0**	**8.0**	**9.0**
Sep	9.0	**5.0**	**5.0**	**5.0**
Oct	5.0	**6.0**	**6.0**	5.0
Nov	29.0	**35.0**	**33.0**	**32.0**
Dec	47.0	**40.0**	**53.0**	**43.0**

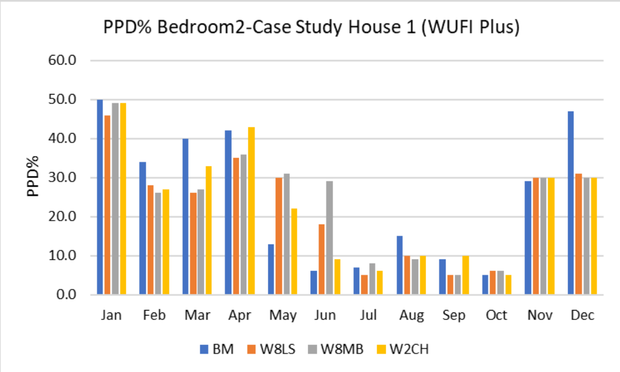
Figure A4-1 PPD%-Bedroom-2-Case Study House-1 (Design-Builder)

b) Bedroom-2 (WUFI Plus Results)

Table 04-0-1 PMV-Bedroom-2-Case Study House-1 (WUFI Plus)

Time	Benchmark		W8-LS		W8-MB		W2CH	
	PMV	Sensation	PMV	Sensation	PMV	Sensation	PMV	Sensation
Jan	-1.6	Cool	-1.4	S-Cool	-1.5	S-Cool	-1.5	S-Cool
Feb	-1.2	S-Cool	-1.0	S-Cool	-1.0	S-Cool	-1.0	S-Cool
Mar	-1.3	S-Cool	-1.0	S-Cool	-1.0	S-Cool	-1.2	S-Cool
Apr	-1.3	S-Cool	-1.2	S-Cool	-1.2	S-Cool	-1.3	S-Cool
May	-0.6	S-Cool	-1.1	S-Cool	-1.1	S-Cool	-0.9	S-Cool
Jun	0.0	Neutral	-0.8	S-Cool	-1.1	S-Cool	0.0	Neutral
Jul	0.0	Neutral	0.0	Neutral	0.0	Neutral	0.0	Neutral
Aug	0.7	S-Warm	0.0	Neutral	0.0	Neutral	0.0	Neutral
Sep	0.0	Neutral	0.0	Neutral	0.0	Neutral	0.5	Neutral
Oct	0.0	Neutral	-0.5	Neutral	0.0	Neutral	0.0	Neutral
Nov	-1.1	S-Cool	-1.1	S-Cool	-1.1	S-Cool	-1.1	S-Cool
Dec	-1.4	S-Cool	-1.1	S-Cool	-1.1	S-Cool	-1.1	S-Cool

Time	BM	W8LS	W8MB	W2CH
Jan	50.0	**46.0**	**49.0**	**49.0**



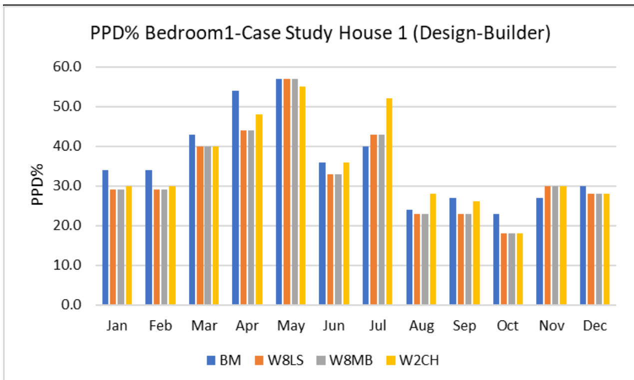
Feb	34.0	28.0	26.0	27.0
Mar	40.0	26.0	27.0	33.0
Apr	42.0	35.0	36.0	43.0
May	13.0	30.0	31.0	22.0
Jun	6.0	18.0	29.0	9.0
Jul	7.0	5.0	8.0	6.0
Aug	15.0	10.0	9.0	10.0
Sep	9.0	5.0	5.0	10.0
Oct	5.0	6.0	6.0	5.0
Nov	29.0	30.0	30.0	30.0
Dec	47.0	31.0	30.0	30.0

Figure A4-2 Bedroom-2-Case Study House-1 (WUFI Plus)

c) Bedroom-1 (Design-Builder Results)

Table A4-3 PMV-Bedroom-1-Case Study House-1 (Design-Builder)

Time	Benchmark		W8-LS		W8-MB		W2CH	
	PMV	Sensation	PMV	Sensation	PMV	Sensation	PMV	Sensation
Jan	-1.2	S-Cool	-1.1	S-Cool	-1.1	S-Cool	-1.1	S-Cool
Feb	-1.2	S-Cool	-1.1	S-Cool	-1.1	S-Cool	-1.1	S-Cool
Mar	-1.3	S-Cool	-1.3	S-Cool	-1.3	S-Cool	-1.3	S-Cool
Apr	-1.6	S-Cool	-1.4	S-Cool	-1.4	S-Cool	-1.5	S-Cool
May	-1.6	S-Cool	-1.6	S-Cool	-1.6	S-Cool	-1.6	S-Cool
Jun	-1.2	S-Cool	-1.2	S-Cool	-1.2	S-Cool	-1.2	S-Cool
Jul	-1.3	S-Cool	-1.4	S-Cool	-1.4	S-Cool	-1.5	S-Cool
Aug	-1.0	S-Cool	-0.9	S-Cool	-0.9	S-Cool	-1.0	S-Cool
Sep	-1.0	S-Cool	-0.9	S-Cool	-0.9	S-Cool	-1.0	S-Cool
Oct	-0.9	S-Cool	-0.8	S-Cool	-0.8	S-Cool	-0.8	S-Cool
Nov	-1.0	S-Cool	-1.1	S-Cool	-1.1	S-Cool	-1.1	S-Cool
Dec	-1.1	S-Cool	-1.0	S-Cool	-1.0	S-Cool	-1.0	S-Cool



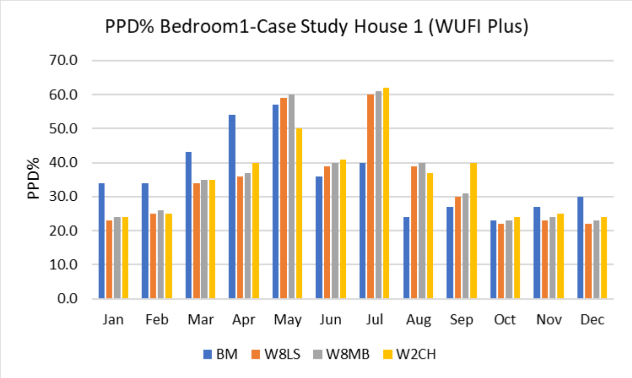
Time	BM	W8LS	W8MB	W2CH
Jan	34.0	29.0	29.0	30.0
Feb	34.0	29.0	29.0	30.0
Mar	43.0	40.0	40.0	40.0
Apr	54.0	44.0	44.0	48.0
May	57.0	57.0	57.0	55.0
Jun	36.0	33.0	33.0	36.0
Jul	40.0	43.0	43.0	52.0
Aug	24.0	23.0	23.0	28.0
Sep	27.0	23.0	23.0	26.0
Oct	23.0	18.0	18.0	18.0
Nov	27.0	30.0	30.0	30.0
Dec	30.0	28.0	28.0	28.0

Figure A4-3 Bedroom-1-Case Study House-1 (Design-Builder)

- **Bedroom-1 (WUFI Plus Results)**

Table A4-4 PMV-Bedroom-2-Case Study House-1 (WUFI Plus)

Time	Benchmark		W8-LS		W8-MB		W2CH	
	PMV	Sensation	PMV	Sensation	PMV	Sensation	PMV	Sensation
Jan	-1.2	S-Cool	-1.0	S-Cool	-1.0	S-Cool	-1.0	S-Cool
Feb	-1.2	S-Cool	-1.0	S-Cool	-1.0	S-Cool	-1.0	S-Cool
Mar	-1.3	S-Cool	-1.2	S-Cool	-1.2	S-Cool	-1.2	S-Cool
Apr	-1.6	S-Cool	-1.3	S-Cool	-1.3	S-Cool	-1.3	S-Cool
May	-1.6	S-Cool	-1.7	S-Cool	-1.7	Cool	-1.5	S-Cool
Jun	-1.2	S-Cool	-1.3	S-Cool	-1.3	S-Cool	-1.3	S-Cool
Jul	-1.3	S-Cool	-1.7	S-Cool	-1.7	Cool	-1.7	S-Cool
Aug	-1.0	S-Cool	-1.3	S-Cool	-1.3	S-Cool	-1.2	S-Cool
Sep	-1.0	S-Cool	-1.1	S-Cool	-1.1	S-Cool	-1.5	S-Cool
Oct	-0.9	S-Cool	-1.0	S-Cool	-1.0	S-Cool	-1.0	S-Cool
Nov	-1.0	S-Cool	-1.0	S-Cool	-1.0	S-Cool	-1.0	S-Cool
Dec	-1.1	S-Cool	-1.0	S-Cool	-1.0	S-Cool	-1.0	S-Cool



Time	BM	W8LS	W8MB	W2CH
Jan	34.0	23.0	24.0	24.0
Feb	34.0	25.0	26.0	25.0
Mar	43.0	34.0	35.0	35.0
Apr	54.0	36.0	37.0	40.0
May	57.0	59.0	60.0	50.0
Jun	36.0	39.0	40.0	41.0
Jul	40.0	60.0	61.0	62.0
Aug	24.0	39.0	40.0	37.0
Sep	27.0	30.0	31.0	40.0
Oct	23.0	22.0	23.0	24.0
Nov	27.0	23.0	24.0	25.0
Dec	30.0	22.0	23.0	24.0

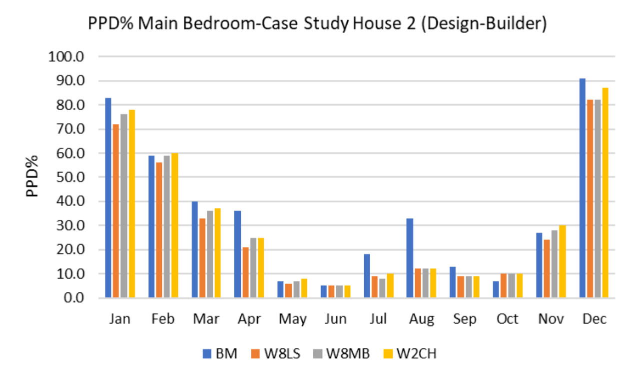
Figure A4-4 Bedroom-1-Case Study House-1 (WUFI Plus)

2- Case Study House 2

- **Main Bedroom (Design-Builder Results)**

Table A4-5 PMV- Master Bedroom -Case Study House-2 (Design-Builder)

Time	Benchmark		W8-LS		W8-MB		W2CH	
	PMV	Sensation	PMV	Sensation	PMV	Sensation	PMV	Sensation
Jan	-2.1	Cool	-1.9	Cool	-2.0	Cool	-2.0	Cool
Feb	-1.8	Cool	-1.6	Cool	-1.6	Cool	-1.7	Cool
Mar	-1.5	S-Cool	-1.2	S-Cool	-1.2	S-Cool	-1.3	S-Cool
Apr	-1.2	S-Cool	-0.9	S-Cool	-0.9	S-Cool	-1.0	S-Cool
May	0.0	Neutral	0.0	Neutral	0.0	Neutral	0.0	Neutral
Jun	0.6	S-Warm	0.0	Neutral	0.0	Neutral	0.0	Neutral
Jul	-1.1	S-Warm	0.0	Neutral	0.0	Neutral	0.0	Neutral
Aug	1.5	S-Warm	0.6	S-Warm	0.6	S-Warm	0.6	S-Warm
Sep	0.8	S-Warm	0.0	Neutral	0.0	Neutral	0.0	Neutral
Oct	0.0	Neutral	0.0	Neutral	0.0	Neutral	0.0	Neutral
Nov	-1.1	S-Cool	-1.0	S-Cool	-1.1	S-Cool	-1.1	S-Cool
Dec	-2.4	Cool	-2.1	Cool	-2.1	Cool	-2.3	Cool



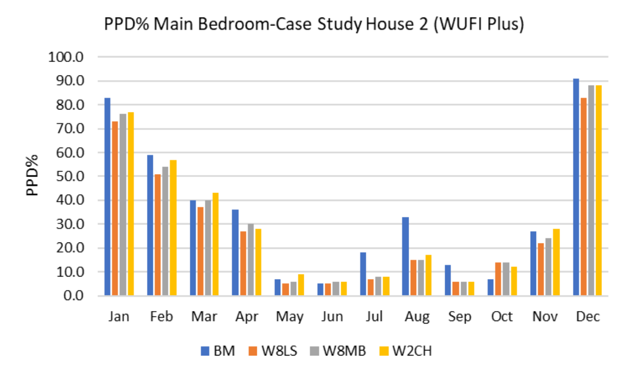
Time	BM	W8LS	W8MB	W2CH
Jan	83.0	72.0	76.0	78.0
Feb	59.0	56.0	59.0	60.0
Mar	40.0	33.0	36.0	37.0
Apr	36.0	21.0	25.0	25.0
May	7.0	6.0	7.0	8.0
Jun	5.0	5.0	5.0	5.0
Jul	18.0	9.0	8.0	10.0
Aug	33.0	12.0	12.0	12.0
Sep	13.0	9.0	9.0	9.0
Oct	7.0	10.0	10.0	10.0
Nov	27.0	24.0	28.0	30.0
Dec	91.0	82.0	82.0	87.0

Figure A4-5 PPD%-Master Bedroom-Case Study House-2 (Design-Builder)

- **Main Bedroom (WUFI Plus Results)**

Table A4-6 PMV- Master Bedroom -Case Study House-2 (WUFI Plus)

Time	Benchmark		W8-LS		W8-MB		W2CH	
	PMV	Sensation	PMV	Sensation	PMV	Sensation	PMV	Sensation
Jan	-2.1	Cool	-1.9	Cool	-2.0	Cool	-2.0	Cool
Feb	-1.8	Cool	-1.6	Cool	-1.7	Cool	-1.7	Cool
Mar	-1.5	S-Cool	-1.4	S-Cool	-1.5	S-Cool	-1.5	S-Cool
Apr	-1.2	S-Cool	-1.0	S-Cool	-1.1	S-Cool	-1.1	S-Cool
May	0.0	Neutral	0.0	Neutral	0.0	Neutral	0.0	Neutral
Jun	0.6	S-Warm	0.0	Neutral	0.0	Neutral	0.0	Neutral
Jul	-1.1	S-Warm	0.6	S-Warm	0.7	S-Warm	0.7	S-Warm
Aug	1.5	S-Warm	-1.1	S-Warm	-1.1	S-Warm	-1.1	S-Warm
Sep	0.8	S-Warm	0.0	Neutral	0.5	S-Warm	0.5	S-Warm
Oct	0.0	Neutral	0.0	Neutral	0.0	Neutral	0.0	Neutral
Nov	-1.1	S-Cool	-0.9	S-Cool	-1.0	S-Cool	-1.0	S-Cool
Dec	-2.4	Cool	-2.2	Cool	-2.3	Cool	-2.3	Cool



Time	BM	W8LS	W8MB	W2CH
Jan	83.0	73.0	76.0	77.0
Feb	59.0	51.0	54.0	57.0
Mar	40.0	37.0	40.0	43.0
Apr	36.0	27.0	30.0	28.0
May	7.0	5.0	6.0	9.0
Jun	5.0	5.0	6.0	6.0
Jul	18.0	7.0	8.0	8.0
Aug	33.0	15.0	15.0	17.0
Sep	13.0	6.0	6.0	6.0
Oct	7.0	14.0	14.0	12.0
Nov	27.0	22.0	24.0	28.0
Dec	91.0	83.0	88.0	88.0

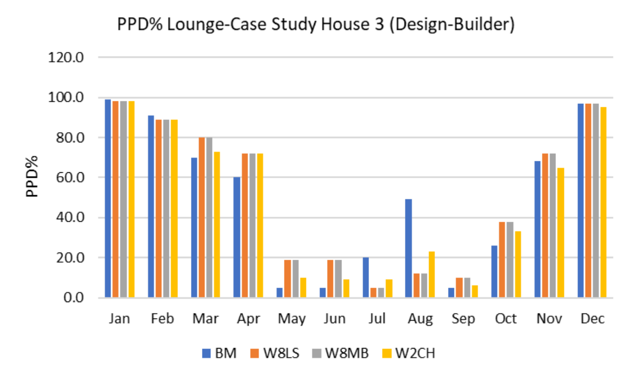
Figure A4-6 Master Bedroom-Case Study House-2 (Design-Builder)

Case Study House 3

- **Lounge (Design-Builder Results)**

Table A4-7 PMV- Lounge -Case Study House-3 (Design-Builder)

Time	Benchmark		W8-LS		W8-MB		W2CH	
	PMV	Sensation	PMV	Sensation	PMV	Sensation	PMV	Sensation
Jan	-2.9	Cold	-2.9	Cold	-2.9	Cold	-2.9	Cold
Feb	-2.4	Cool	-2.3	Cool	-2.3	Cool	-2.3	Cool
Mar	-1.9	Cool	-2.0	Cool	-2.0	Cool	-1.9	Cool
Apr	-1.7	Cool	-1.9	Cool	-1.9	Cool	-1.9	Cool
May	0.0	Neutral	-0.8	S-Cool	-0.8	S-Cool	0.0	Neutral
Jun	0.0	Neutral	-0.7	S-Cool	-0.7	S-Cool	0.0	Neutral
Jul	0.9	S-Warm	0.0	Neutral	0.0	Neutral	0.0	Neutral
Aug	1.5	S-Warm	0.5	S-Warm	0.5	S-Warm	0.9	S-Warm
Sep	0.6	S-Warm	-0.5	S-Cool	-0.5	S-Cool	0.0	Neutral
Oct	-1.0	S-Cool	-2.8	Cold	-2.8	Cold	-1.1	S-Cool
Nov	-1.8	Cool	-1.9	Cool	-1.9	Cool	1.8	Cool
Dec	-2.7	Cold	-2.7	Cold	-2.7	Cold	-2.6	Cold



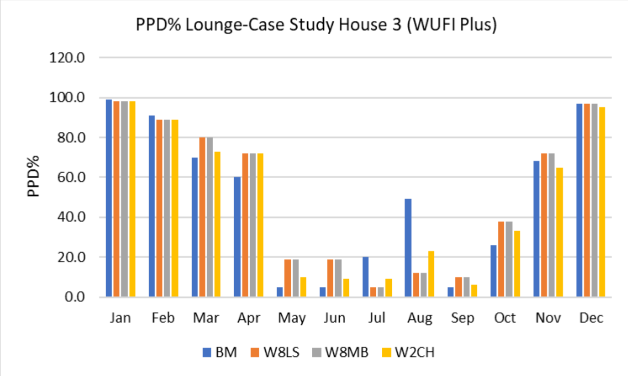
Time	BM	W8LS	W8MB	W2CH
Jan	99.0	98.0	98.0	98.0
Feb	91.0	89.0	89.0	89.0
Mar	70.0	80.0	80.0	73.0
Apr	60.0	72.0	72.0	72.0
May	5.0	19.0	19.0	10.0
Jun	5.0	19.0	19.0	9.0
Jul	20.0	5.0	5.0	9.0
Aug	49.0	12.0	12.0	23.0
Sep	5.0	10.0	10.0	6.0
Oct	26.0	38.0	38.0	33.0
Nov	68.0	72.0	72.0	65.0
Dec	97.0	97.0	97.0	95.0

Figure A4-7 PPD%-Lounge-Case Study House-3 (Design-Builder)

- **Lounge (WUFI Plus Results)**

Table A4-8 PMV- Lounge -Case Study House-3 (WUFI Plus)

Time	Benchmark		W8-LS		W8-MB		W2CH	
	PMV	Sensation	PMV	Sensation	PMV	Sensation	PMV	Sensation
Jan	-2.9	Cold	-2.9	Cold	-2.9	Cold	-2.8	Cold
Feb	-2.4	Cool	-2.3	Cool	-2.3	Cool	-2.1	Cool
Mar	-1.9	Cool	-2.0	Cool	-2.0	Cool	-1.7	Cool
Apr	-1.7	Cool	-1.5	Cool	-1.9	Cool	-1.5	Cool
May	0.0	Neutral	-0.8	S-Cool	-0.8	S-Cool	0.0	Neutral
Jun	0.0	Neutral	-0.7	S-Cool	-0.7	S-Cool	0.0	Neutral
Jul	0.9	S-Warm	0.0	Neutral	0.0	Neutral	0.0	Neutral
Aug	1.5	S-Warm	0.5	S-Warm	0.5	S-Warm	0.9	S-Warm
Sep	0.6	S-Warm	-0.5	S-Cool	-0.5	S-Cool	0.0	Neutral
Oct	-1.0	S-Cool	-2.7	Cold	-2.7	Cold	-1.1	S-Cool
Nov	-1.8	Cool	-1.8	Cool	-1.7	Cool	1.8	Cool
Dec	-2.7	Cold	-2.7	Cold	-2.8	Cold	-2.7	Cold



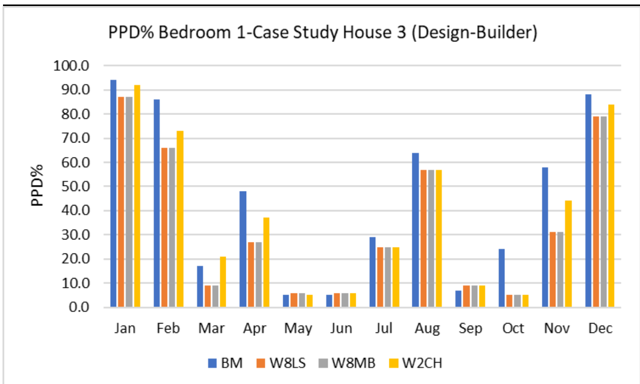
Time	BM	W8LS	W8MB	W2CH
Jan	99.0	98.0	98.0	98.0
Feb	91.0	89.0	89.0	89.0
Mar	70.0	80.0	80.0	73.0
Apr	60.0	72.0	72.0	72.0
May	5.0	19.0	19.0	10.0
Jun	5.0	19.0	19.0	9.0
Jul	20.0	5.0	5.0	9.0
Aug	49.0	12.0	12.0	23.0
Sep	5.0	10.0	10.0	6.0
Oct	26.0	38.0	38.0	33.0
Nov	68.0	72.0	72.0	65.0
Dec	97.0	97.0	97.0	95.0

Figure A4-8 Lounge-Case Study House-3 (WUFI Plus)

- **Bedroom-1 (Design-Builder Results)**

Table A4-9 PMV- Bedroom-1-Case Study House-3 (Design-Builder)

Time	Benchmark		W8-LS		W8-MB		W2CH	
	PMV	Sensation	PMV	Sensation	PMV	Sensation	PMV	Sensation
Jan	-2.5	Cold	-2.3	Cool	-2.4	Cool	-2.4	Cool
Feb	-2.2	Cool	-1.8	Cool	-1.8	Cool	-1.9	Cool
Mar	-0.7	S-Cool	0.0	Neutral	0.0	Neutral	-0.9	S-Cool
Apr	-1.4	S-Cool	-1.0	S-Cool	-1.0	S-Cool	-1.2	S-Cool
May	0.0	Neutral	0.0	Neutral	0.0	Neutral	0.0	Neutral
Jun	0.0	Neutral	0.0	Neutral	0.0	Neutral	0.0	Neutral
Jul	1.0	S-Warm	1.0	S-Warm	1.1	S-Warm	1.2	S-Warm
Aug	1.8	Warm	1.6	S-Warm	1.6	S-Warm	1.6	S-Warm
Sep	0.0	Neutral	0.0	Neutral	0.0	Neutral	0.0	Neutral
Oct	-0.9	S-Cool	0.0	Neutral	0.0	Neutral	0.0	Neutral
Nov	-1.6	Cool	-1.0	S-Cool	-1.0	S-Cool	-1.1	S-Cool
Dec	-2.6	Cold	-2.0	Cool	-2.0	Cool	-2.0	Cool



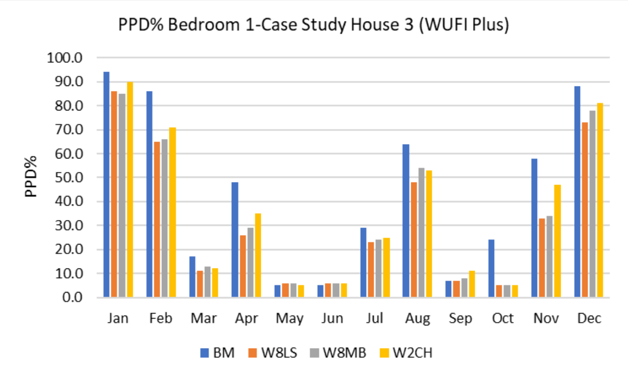
Time	BM	W8LS	W8MB	W2CH
Jan	94.0	87.0	87.0	92.0
Feb	86.0	66.0	66.0	73.0
Mar	17.0	9.0	9.0	21.0
Apr	48.0	27.0	27.0	37.0
May	5.0	6.0	6.0	5.0
Jun	5.0	6.0	6.0	6.0
Jul	29.0	25.0	25.0	25.0
Aug	64.0	57.0	57.0	57.0
Sep	7.0	9.0	9.0	9.0
Oct	24.0	5.0	5.0	5.0
Nov	58.0	31.0	31.0	44.0
Dec	88.0	79.0	79.0	84.0

Figure A4-9 PPD%-Bedroom-1-Case Study House-3 (Design-Builder)

- **Bedroom-1 (WUFI Plus Results)**

Table A4-10 PMV- Bedroom-1-Case Study House-3 (WUFI Plus)

Time	Benchmark		W8-LS		W8-MB		W2CH	
	PMV	Sensation	PMV	Sensation	PMV	Sensation	PMV	Sensation
Jan	-2.5	Cold	-2.3	Cool	-2.3	Cool	-2.4	Cool
Feb	-2.2	Cool	-1.8	Cool	-1.8	Cool	-1.9	Cool
Mar	-0.7	S-Cool	0.0	Neutral	0.0	Neutral	-0.9	S-Cool
Apr	-1.4	S-Cool	-1.0	S-Cool	-1.0	S-Cool	-1.2	S-Cool
May	0.0	Neutral	0.0	Neutral	0.0	Neutral	0.0	Neutral
Jun	0.0	Neutral	0.0	Neutral	0.0	Neutral	0.0	Neutral
Jul	1.0	S-Warm	1.0	S-Warm	1.0	S-Warm	1.0	S-Warm
Aug	1.8	Warm	1.6	S-Warm	1.6	S-Warm	1.6	S-Warm
Sep	0.0	Neutral	0.0	Neutral	0.0	Neutral	0.0	Neutral
Oct	-0.9	S-Cool	0.0	Neutral	0.0	Neutral	0.0	Neutral
Nov	-1.6	Cool	-1.0	S-Cool	-1.0	S-Cool	-1.3	S-Cool
Dec	-2.6	Cold	-2.0	Cool	-2.0	Cool	-2.0	Cool



Time	BM	W8LS	W8MB	W2CH
Jan	94.0	86.0	85.0	90.0
Feb	86.0	65.0	66.0	71.0
Mar	17.0	11.0	13.0	12.0
Apr	48.0	26.0	29.0	35.0
May	5.0	6.0	6.0	5.0
Jun	5.0	6.0	6.0	6.0
Jul	29.0	23.0	24.0	25.0
Aug	64.0	48.0	54.0	53.0
Sep	7.0	7.0	8.0	11.0
Oct	24.0	5.0	5.0	5.0
Nov	58.0	33.0	34.0	47.0
Dec	88.0	73.0	78.0	81.0

Figure A4-10 PPD%-Bedroom-1-Case Study House-3 (WUFI Plus)

A5-Indoor Temperature and Relative Humidity

A5-1Case Study House 1-Living room

W2CH			
RH%			
Time	Bench Mark	Design-Builder	WUFI Plus
Jan	44.4	0.2	0.2
Feb	44.7	-0.1	-0.2
Mar	45.5	0.1	-1.0
Apr	40.0	0.3	-0.9
May	36.7	0.6	-0.1
Jun	39.4	0.8	-0.1
Jul	43.3	0.9	-0.2
Aug	48.8	1.0	-0.2
Sep	60.9	1.7	-1.2
Oct	51.6	0.8	-1.1
Nov	69.6	0.7	-0.2
Dec	57.6	0.1	-0.1

W2CH			
Air Temperature °C			
Time	Bench Mark	Design-Builder	WUFI Plus
Jan	17.3	0.8	1.1
Feb	18.0	0.9	1.1
Mar	18.4	-0.1	0.8
Apr	21.5	0.0	0.5
May	24.1	-0.6	-0.6
Jun	24.9	-0.7	-0.1
Jul	26.8	-0.3	-0.4
Aug	28.0	-0.8	-0.4
Sep	26.6	-0.7	-0.4
Oct	24.1	-0.4	-0.4
Nov	18.2	0.5	0.3
Dec	16.5	0.3	0.4

W2CH			
Radiant Temperature °C			
Time	Bench Mark	Design-Builder	WUFI Plus
Jan	15.2	0.5	1.8
Feb	16.5	0.4	2.3
Mar	17.2	0.3	1.1
Apr	19.7	0.0	1.7
May	23.7	-0.4	0.7
Jun	24.5	-0.4	0.1
Jul	26.2	-0.5	-0.5
Aug	27.1	-0.4	-0.4
Sep	26.1	-0.6	-0.2
Oct	23.7	-0.2	-0.4
Nov	18.8	-0.2	0.0
Dec	16.1	0.3	0.3

W2CH			
Operative Temperature°C			
Time	Bench Mark	Design-Builder	WUFI Plus
Jan	16.2	0.6	1.4
Feb	17.2	0.6	1.7
Mar	17.8	0.1	0.9
Apr	20.6	0.0	1.1
May	23.9	-0.5	0.0
Jun	24.7	-0.6	0.0
Jul	26.5	-0.4	-0.5
Aug	27.5	-0.6	-0.4
Sep	26.3	-0.6	-0.3
Oct	23.9	-0.3	-0.4
Nov	18.5	0.2	0.2
Dec	16.3	0.3	0.4

W8LS			
RH%			
Time	Bench Mark	Design-Builder	WUFI Plus
Jan	44.4	-0.1	0.2
Feb	44.7	-0.2	-0.2
Mar	45.5	0.3	-1.1
Apr	40.0	0.6	-0.9
May	36.7	1.3	-0.1
Jun	39.4	1.6	-0.1
Jul	43.3	2.1	-0.1
Aug	48.8	2.4	-0.2
Sep	60.9	3.6	-1.2

W8LS			
Air Temperature °C			
Time	Bench Mark	Design-Builder	WUFI Plus
Jan	17.3	1.2	1.5
Feb	18.0	1.3	1.5
Mar	18.4	0.3	1.2
Apr	21.5	0.4	0.9
May	24.1	-1.0	-1.0
Jun	24.9	-1.1	-0.5
Jul	26.8	-0.7	-0.8
Aug	28.0	-1.2	-0.8
Sep	26.6	-1.1	-0.8

W8LS			
Radiant Temperature °C			
Time	Bench Mark	Design-Builder	WUFI Plus
Jan	15.2	1.1	2.0
Feb	16.5	0.9	1.6
Mar	17.2	0.6	1.8
Apr	19.7	0.2	0.7
May	23.7	-0.8	-1.2
Jun	24.5	-0.8	-0.2
Jul	26.2	-1.0	-0.8
Aug	27.1	-0.9	-0.7
Sep	26.1	-1.1	-0.3

W8LS			
Operative Temperature°C			
Time	Bench Mark	Design-Builder	WUFI Plus
Jan	16.2	1.2	1.8
Feb	17.2	1.1	1.5
Mar	17.8	0.5	1.5
Apr	20.6	0.3	0.8
May	23.9	-0.9	-1.1
Jun	24.7	-1.0	-0.4
Jul	26.5	-0.8	-0.8
Aug	27.5	-1.1	-0.7
Sep	26.3	-1.1	-0.5

Oct	51.6	2.3	-1.1
Nov	69.6	1.7	-0.2
Dec	57.6	0.2	-0.1

Oct	24.1	-0.8	-0.8
Nov	18.2	0.9	-0.7
Dec	16.5	0.7	0.8

Oct	23.7	-0.6	-0.5
Nov	18.8	-0.5	-0.1
Dec	16.1	0.7	0.3

Oct	23.9	-0.7	-0.7
Nov	18.5	0.2	-0.4
Dec	16.3	0.7	0.6

W8MB			
RH%			
Time	Bench Mark	Design-Builder	WUFI Plus
Jan	44.4	0.0	0.2
Feb	44.7	-0.2	-0.2
Mar	45.5	0.3	2.6
Apr	40.0	0.5	1.1
May	36.7	1.2	0.0
Jun	39.4	1.6	-0.1
Jul	43.3	2.0	-0.1
Aug	48.8	2.3	-0.2
Sep	60.9	3.5	-1.1
Oct	51.6	2.1	-1.1
Nov	69.6	1.6	-0.1
Dec	57.6	0.2	-0.1

W8MB			
Air Temperature°C			
Time	Bench Mark	Design-Builder	WUFI Plus
Jan	17.3	1.0	1.3
Feb	18.0	1.1	1.4
Mar	18.4	0.2	1.0
Apr	21.5	0.2	0.7
May	24.1	-1.2	-1.1
Jun	24.9	-1.0	-0.4
Jul	26.8	-0.6	-0.7
Aug	28.0	-1.0	-0.6
Sep	26.6	-1.0	-0.6
Oct	24.1	-0.6	-0.7
Nov	18.2	1.0	-0.5
Dec	16.5	0.6	0.7

W8MB			
Radiant Temperature°C			
Time	Bench Mark	Design-Builder	WUFI Plus
Jan	15.2	1.1	2.4
Feb	16.5	0.8	3.1
Mar	17.2	0.6	1.5
Apr	19.7	0.1	2.3
May	23.7	-0.8	1.0
Jun	24.5	-0.8	0.1
Jul	26.2	-0.9	-0.8
Aug	27.1	-0.9	-0.7
Sep	26.1	-1.1	-0.3
Oct	23.7	-0.6	-0.5
Nov	18.8	-0.4	0.0
Dec	16.1	0.7	0.3

W8MB			
Operative Temperature°C			
Time	Bench Mark	Design-Builder	WUFI Plus
Jan	16.2	1.1	1.9
Feb	17.2	1.0	2.2
Mar	17.8	0.4	1.3
Apr	20.6	0.2	1.5
May	23.9	-1.0	-0.1
Jun	24.7	-0.9	-0.1
Jul	26.5	-0.8	-0.7
Aug	27.5	-1.0	-0.7
Sep	26.3	-1.0	-0.4
Oct	23.9	-0.6	-0.6
Nov	18.5	0.3	-0.3
Dec	16.3	0.6	0.5

A5-2Case Study House 1-Bedroom 2

W2CH			
RH%			
Time	Bench Mark	Design-Builder	WUFI Plus
Jan	39.7	0.1	9.2
Feb	36.7	0.3	7.0
Mar	43.1	0.3	-0.7
Apr	39.4	0.6	0.2
May	34.4	0.4	2.3
Jun	49.5	0.9	0.5
Jul	45.1	0.9	2.0

W2CH			
Air Temperature°C			
Time	Bench Mark	Design-Builder	WUFI Plus
Jan	19.1	0.2	0.1
Feb	20.8	0.3	0.5
Mar	19.2	0.2	0.6
Apr	21.6	-0.3	0.0
May	25.0	-0.3	-0.5
Jun	25.6	-0.7	-0.5
Jul	27.2	-0.8	0.1

W2CH			
Radiant Temperature°C			
Time	Bench Mark	Design-Builder	WUFI Plus
Jan	16.1	0.2	0.1
Feb	17.7	0.3	0.5
Mar	17.9	0.2	0.6
Apr	20.2	-0.3	0.0
May	24.4	-0.3	-0.5
Jun	25.2	-0.7	-0.5
Jul	26.8	-0.8	0.1

W2CH			
Operative Temperature°C			
Time	Bench Mark	Design-Builder	WUFI Plus
Jan	17.6	0.2	0.1
Feb	19.2	0.3	0.5
Mar	18.6	0.2	0.6
Apr	20.9	-0.3	0.0
May	24.7	-0.3	-0.5
Jun	25.4	-0.7	-0.5
Jul	27.0	-0.8	0.1

Aug	48.3	1.2	0.8
Sep	60.0	1.6	-1.3
Oct	55.4	1.0	0.0
Nov	69.0	0.7	-0.1
Dec	49.9	0.3	-0.4

Aug	28.2	-0.7	-0.4
Sep	27.1	-0.8	0.2
Oct	25.1	-0.4	-0.4
Nov	18.4	-0.3	-0.1
Dec	18.7	0.3	0.8

Aug	27.8	-0.7	-0.4
Sep	26.9	-0.8	0.2
Oct	24.5	-0.4	-0.4
Nov	19.4	-0.3	-0.1
Dec	17.0	0.3	0.8

Aug	28.0	-0.7	-0.4
Sep	27.0	-0.8	0.2
Oct	24.8	-0.4	-0.4
Nov	18.9	-0.3	-0.1
Dec	17.9	0.3	0.8

W8LS			
RH%			
Time	Bench Mark	Design-Builder	WUFI Plus
Jan	39.7	0.3	9.4
Feb	36.7	0.5	0.1
Mar	43.1	0.4	-11.2
Apr	39.4	0.8	-3.8
May	34.4	0.9	-2.8
Jun	49.5	2.1	-2.9
Jul	45.1	2.5	-5.7
Aug	48.3	3.1	-2.4
Sep	60.0	4.0	-1.9
Oct	55.4	2.0	-0.5
Nov	69.0	1.8	-0.1
Dec	49.9	0.6	-1.7

W8LS			
Air Temperature°C			
Time	Bench Mark	Design-Builder	WUFI Plus
Jan	19.1	0.4	0.4
Feb	20.8	0.4	0.5
Mar	19.2	0.7	1.3
Apr	21.6	-0.4	0.5
May	25.0	-0.9	-1.4
Jun	25.6	-1.6	-1.4
Jul	27.2	-1.2	-0.4
Aug	28.2	-1.1	-0.6
Sep	27.1	-1.2	-0.8
Oct	25.1	-0.6	-0.5
Nov	18.4	-0.5	-0.1
Dec	18.7	0.4	1.3

W8LS			
Radiant Temperature°C			
Time	Bench Mark	Design-Builder	WUFI Plus
Jan	16.1	0.4	0.4
Feb	17.7	0.4	0.5
Mar	17.9	0.7	1.3
Apr	20.2	-0.4	0.5
May	24.4	-0.9	-1.4
Jun	25.2	-1.6	-1.4
Jul	26.8	-1.2	-0.4
Aug	27.8	-1.1	-0.6
Sep	26.9	-1.2	-0.8
Oct	24.5	-0.6	-0.5
Nov	19.4	-0.5	-0.1
Dec	17.0	0.4	1.3

W8LS			
Operative Temperature°C			
Time	Bench Mark	Design-Builder	WUFI Plus
Jan	17.6	0.4	0.4
Feb	19.2	0.4	0.5
Mar	18.6	0.7	1.3
Apr	20.9	-0.4	0.5
May	24.7	-0.9	-1.4
Jun	25.4	-1.6	-1.4
Jul	27.0	-1.2	-0.4
Aug	28.0	-1.1	-0.6
Sep	27.0	-1.2	-0.8
Oct	24.8	-0.6	-0.5
Nov	18.9	-0.5	-0.1
Dec	17.9	0.4	1.3

W8MB			
RH%			
Time	Bench Mark	Design-Builder	WUFI Plus
Jan	39.7	0.3	10.0
Feb	36.7	0.4	4.1
Mar	43.1	0.4	-8.0
Apr	39.4	0.8	-2.9
May	34.4	0.8	-1.5
Jun	49.5	2.0	-1.7
Jul	45.1	2.4	-2.4
Aug	48.3	3.0	-0.9

W8MB			
Air Temperature°C			
Time	Bench Mark	Design-Builder	WUFI Plus
Jan	19.1	0.3	0.2
Feb	20.8	0.4	0.5
Mar	19.2	-0.6	1.1
Apr	21.6	0.3	0.4
May	25.0	-0.7	-1.3
Jun	25.6	-1.0	-2.2
Jul	27.2	-1.1	0.3
Aug	28.2	-1.1	-0.6

W8MB			
Radiant Temperature°C			
Time	Bench Mark	Design-Builder	WUFI Plus
Jan	16.1	0.3	0.2
Feb	17.7	0.4	0.5
Mar	17.9	-0.6	1.1
Apr	20.2	0.3	0.4
May	24.4	-0.7	-1.3
Jun	25.2	-1.0	-2.2
Jul	26.8	-1.1	0.3
Aug	27.8	-1.1	-0.6

W8MB			
Operative Temperature°C			
Time	Bench Mark	Design-Builder	WUFI Plus
Jan	17.6	0.3	0.2
Feb	19.2	0.4	0.5
Mar	18.6	-0.6	1.1
Apr	20.9	0.3	0.4
May	24.7	-0.7	-1.3
Jun	25.4	-1.0	-2.2
Jul	27.0	-1.1	0.3
Aug	28.0	-1.1	-0.6

Sep	60.0	3.9	-1.8	Sep	27.1	-1.2	-0.6	Sep	26.9	-1.2	-0.6	Sep	27.0	-1.2	-0.6
Oct	55.4	1.9	-0.5	Oct	25.1	-0.6	-0.4	Oct	24.5	-0.6	-0.4	Oct	24.8	-0.6	-0.4
Nov	69.0	1.6	-0.1	Nov	18.4	-0.4	-0.1	Nov	19.4	-0.4	-0.1	Nov	18.9	-0.4	-0.1
Dec	49.9	0.6	-1.4	Dec	18.7	-0.4	1.2	Dec	17.0	-0.4	1.2	Dec	17.9	-0.4	1.2

A5-3 Case Study House 1-Bedroom 1

W2CH				W2CH				W2CH				W2CH			
RH%				**Air Temperature°C**				**Radiant Temperature°C**				**Operative Temperature°C**			
Time	Bench Mark	Design-Builder	WUFI Plus	Time	Bench Mark	Design-Builder	WUFI Plus	Time	Bench Mark	Design-Builder	WUFI Plus	Time	Bench Mark	Design-Builder	WUFI Plus
Jan	60.9	1.0	2.6	Jan	21.8	-0.5	-2.9	Jan	16.2	0.5	2.7	Jan	19.0	0.0	2.6
Feb	60.4	0.7	4.0	Feb	21.1	-0.3	-0.5	Feb	16.9	0.3	1.4	Feb	19.0	0.0	1.2
Mar	57.1	0.3	-4.8	Mar	19.4	-0.1	-0.3	Mar	17.2	0.1	0.8	Mar	18.3	0.0	0.7
Apr	46.5	0.7	3.6	Apr	20.9	-0.2	0.5	Apr	19.7	-0.2	0.7	Apr	20.3	0.2	0.6
May	39.2	-2.4	0.1	May	20.5	0.7	4.1	May	23.1	-0.3	0.1	May	21.8	-0.2	0.2
Jun	25.3	-2.0	1.1	Jun	22.1	0.6	3.0	Jun	24.3	-0.4	-0.3	Jun	23.2	-0.1	-0.1
Jul	22.6	-3.4	2.2	Jul	20.5	1.2	6.2	Jul	24.9	-0.2	-0.5	Jul	22.7	-0.5	-0.3
Aug	47.5	-3.0	0.2	Aug	21.2	1.2	6.5	Aug	25.6	-0.2	-0.6	Aug	23.4	-0.5	-0.3
Sep	54.0	-1.3	-0.8	Sep	21.5	0.5	5.0	Sep	24.7	-0.4	-0.7	Sep	23.1	-0.1	-0.5
Oct	74.4	-1.0	-1.3	Oct	21.5	0.6	3.2	Oct	22.9	-0.1	-0.5	Oct	22.2	-0.3	-0.4
Nov	60.4	0.6	-0.8	Nov	19.2	0.0	-1.0	Nov	18.9	0.0	0.2	Nov	19.0	0.0	0.3
Dec	66.4	0.6	-0.6	Dec	21.0	-0.3	-2.5	Dec	17.0	0.3	1.4	Dec	19.0	0.0	1.4

W8LS				W8LS				W8LS				W8LS			
RH%				**Air Temperature°C**				**Radiant Temperature°C**				**Operative Temperature°C**			
Time	Bench Mark	Design-Builder	WUFI Plus	Time	Bench Mark	Design-Builder	WUFI Plus	Time	Bench Mark	Design-Builder	WUFI Plus	Time	Bench Mark	Design-Builder	WUFI Plus
Jan	60.9	1.9	-6.1	Jan	21.8	-0.9	8.0	Jan	16.2	0.9	8.1	Jan	19.0	0.0	8.0
Feb	60.4	1.3	-6.8	Feb	21.1	-0.6	4.0	Feb	16.9	0.6	4.6	Feb	19.0	0.0	4.3
Mar	57.1	0.5	-11.7	Mar	19.4	-0.2	2.5	Mar	17.2	0.3	2.8	Mar	18.3	-0.1	2.6
Apr	46.5	1.1	-5.0	Apr	20.9	-0.4	3.0	Apr	19.7	-0.3	3.3	Apr	20.3	0.4	3.2
May	39.2	-2.4	-3.3	May	20.5	0.6	1.1	May	23.1	-1.0	0.7	May	21.8	0.2	0.9
Jun	25.3	-1.2	0.4	Jun	22.1	0.3	0.0	Jun	24.3	-1.2	-0.5	Jun	23.2	0.5	-0.3

Time	Bench Mark	Design-Builder	WUFI Plus
Jul	22.6	-2.4	-0.5
Aug	47.5	-2.3	-0.5
Sep	54.0	-0.3	-1.1
Oct	74.4	-0.9	-1.7
Nov	60.4	0.8	-1.0
Dec	66.4	1.4	-4.1

Time	Bench Mark	Design-Builder	WUFI Plus
Jul	20.5	0.7	-0.1
Aug	21.2	0.8	-0.1
Sep	21.5	0.2	-0.4
Oct	21.5	0.6	-0.3
Nov	19.2	0.0	0.4
Dec	21.0	-0.5	3.9

Time	Bench Mark	Design-Builder	WUFI Plus
Jul	24.9	-1.3	-0.9
Aug	25.6	-1.3	-1.1
Sep	24.7	-1.1	-1.0
Oct	22.9	-0.6	-0.8
Nov	18.9	-0.1	0.3
Dec	17.0	0.5	4.0

Time	Bench Mark	Design-Builder	WUFI Plus
Jul	22.7	0.3	-0.5
Aug	23.4	0.2	-0.6
Sep	23.1	0.4	-0.7
Oct	22.2	0.0	-0.6
Nov	19.0	0.0	0.4
Dec	19.0	0.0	3.9

W8MB			
RH%			
Time	Bench Mark	Design-Builder	WUFI Plus
Jan	60.9	1.9	-3.0
Feb	60.4	1.2	-1.3
Mar	57.1	0.5	-9.9
Apr	46.5	1.1	-4.2
May	39.2	-2.4	-2.3
Jun	25.3	-1.3	0.5
Jul	22.6	-2.4	1.3
Aug	47.5	-2.3	0.0
Sep	54.0	-0.3	-0.9
Oct	74.4	-0.9	-1.4
Nov	60.4	0.8	-0.9
Dec	66.4	1.3	-3.6

W8MB			
Air Temperature°C			
Time	Bench Mark	Design-Builder	WUFI Plus
Jan	21.8	-0.9	7.2
Feb	21.1	-0.6	3.5
Mar	19.4	-0.2	2.2
Apr	20.9	-0.4	2.6
May	20.5	0.6	1.0
Jun	22.1	0.3	0.0
Jul	20.5	0.8	-0.1
Aug	21.2	0.8	-0.1
Sep	21.5	0.3	-0.4
Oct	21.5	0.6	-0.3
Nov	19.2	0.0	0.4
Dec	21.0	-0.5	3.7

W8MB			
Radiant Temperature°C			
Time	Bench Mark	Design-Builder	WUFI Plus
Jan	16.2	0.9	7.3
Feb	16.9	0.6	4.0
Mar	17.2	0.3	2.5
Apr	19.7	-0.3	2.9
May	23.1	-1.0	0.6
Jun	24.3	-1.1	-0.5
Jul	24.9	-1.2	-0.9
Aug	25.6	-1.2	-1.0
Sep	24.7	-1.1	-1.0
Oct	22.9	-0.5	-0.8
Nov	18.9	-0.1	0.3
Dec	17.0	0.5	3.7

W8MB			
Operative Temperature°C			
Time	Bench Mark	Design-Builder	WUFI Plus
Jan	19.0	0.0	7.2
Feb	19.0	0.0	3.7
Mar	18.3	-0.1	2.4
Apr	20.3	0.4	2.8
May	21.8	0.2	0.8
Jun	23.2	0.4	-0.3
Jul	22.7	0.2	-0.5
Aug	23.4	0.2	-0.6
Sep	23.1	0.4	-0.7
Oct	22.2	0.0	-0.6
Nov	19.0	0.0	0.4
Dec	19.0	0.0	3.7

A5-4 Case Study House 3-Living room

W2CH			
RH%			
Time	Bench Mark	Design-Builder	WUFI Plus
Jan	60.9	-0.8	-0.2
Feb	60.4	-0.5	0.3
Mar	57.1	-0.1	0.1
Apr	46.5	0.4	-0.1

W2CH			
Air Temperature°C			
Time	Bench Mark	Design-Builder	WUFI Plus
Jan	11.3	0.2	0.1
Feb	13.3	0.2	0.0
Mar	15.4	0.1	0.0
Apr	20.2	-0.1	0.1

W2CH			
Radiant Temperature°C			
Time	Bench Mark	Design-Builder	WUFI Plus
Jan	11.3	0.3	0.1
Feb	13.3	0.2	0.0
Mar	15.4	0.1	0.0
Apr	20.2	-0.2	0.1

W2CH			
Operative Temperature°C			
Time	Bench Mark	Design-Builder	WUFI Plus
Jan	12.2	0.2	0.1
Feb	14.2	0.2	0.0
Mar	16.3	0.1	0.0
Apr	20.4	-0.2	0.1

May	39.2	0.8	0.0	May	26.4	-0.4	0.0	May	26.4	-0.5	0.0	May	26.0	-0.5	0.0
Jun	25.3	0.2	0.0	Jun	29.0	-0.1	0.0	Jun	29.0	0.0	0.0	Jun	27.9	-0.1	0.0
Jul	22.6	0.1	-0.4	Jul	30.9	-0.1	0.2	Jul	30.9	0.0	0.2	Jul	29.7	-0.1	0.2
Aug	47.5	1.4	-0.1	Aug	31.2	-0.5	0.0	Aug	31.2	-0.6	0.0	Aug	30.3	-0.6	0.0
Sep	54.0	-0.2	-0.5	Sep	28.7	0.1	0.1	Sep	28.7	0.2	0.1	Sep	27.6	0.1	0.1
Oct	74.4	-0.4	-0.4	Oct	23.2	0.1	0.0	Oct	23.2	0.2	0.0	Oct	22.7	0.1	0.0
Nov	60.4	-0.9	-0.2	Nov	15.5	0.3	0.0	Nov	15.5	0.3	0.0	Nov	16.2	0.3	0.0
Dec	66.4	-1.2	-0.5	Dec	11.9	0.3	0.1	Dec	11.9	0.4	0.1	Dec	12.9	0.4	0.1

W8LS				W8LS				W8LS				W8LS			
RH%				**Air Temperature°C**				**Radiant Temperature°C**				**Operative Temperature°C**			
Time	Bench Mark	Design-Builder	WUFI Plus	Time	Bench Mark	Design-Builder	WUFI Plus	Time	Bench Mark	Design-Builder	WUFI Plus	Time	Bench Mark	Design-Builder	WUFI Plus
Jan	60.9	-1.6	-0.4	Jan	11.3	0.5	0.1	Jan	11.3	0.6	0.1	Jan	12.2	0.6	0.1
Feb	60.4	-1.0	-0.2	Feb	13.3	0.4	0.1	Feb	13.3	0.4	0.1	Feb	14.2	0.4	0.1
Mar	57.1	-0.1	-0.4	Mar	15.4	0.1	0.1	Mar	15.4	0.1	0.1	Mar	16.3	0.1	0.1
Apr	46.5	0.7	-1.1	Apr	20.2	-0.3	0.5	Apr	20.2	-0.3	0.5	Apr	20.4	-0.3	0.5
May	39.2	1.8	-0.3	May	26.4	-0.9	0.1	May	26.4	-1.0	0.1	May	26.0	-0.9	0.1
Jun	25.3	-0.3	-0.3	Jun	29.0	0.2	0.2	Jun	29.0	0.3	0.2	Jun	27.9	0.2	0.2
Jul	22.6	-0.4	-1.1	Jul	30.9	0.2	0.5	Jul	30.9	0.3	0.5	Jul	29.7	0.2	0.6
Aug	47.5	2.7	-0.4	Aug	31.2	-1.0	0.2	Aug	31.2	-1.1	0.2	Aug	30.3	-1.1	0.2
Sep	54.0	-0.6	-0.6	Sep	28.7	0.2	0.2	Sep	28.7	0.3	0.2	Sep	27.6	0.3	0.2
Oct	74.4	-0.8	-0.2	Oct	23.2	0.3	0.0	Oct	23.2	0.3	0.0	Oct	22.7	0.3	0.0
Nov	60.4	-0.9	-0.2	Nov	15.5	0.3	0.0	Nov	15.5	0.3	0.0	Nov	16.2	0.3	0.0
Dec	66.4	-1.8	-0.7	Dec	11.9	0.5	0.1	Dec	11.9	0.6	0.1	Dec	12.9	0.6	0.2

W8MB				W8MB				W8MB				W8MB			
RH%				**Air Temperature °C**				**Radiant Temperature °C**				**Operative Temperature °C**			
Time	Bench Mark	Design-Builder	WUFI Plus	Time	Bench Mark	Design-Builder	WUFI Plus	Time	Bench Mark	Design-Builder	WUFI Plus	Time	Bench Mark	Design-Builder	WUFI Plus
Jan	60.9	-1.5	-0.5	Jan	11.3	0.5	0.1	Jan	11.3	0.6	0.1	Jan	12.2	0.5	0.1
Feb	60.4	-0.9	0.1	Feb	13.3	0.3	0.0	Feb	13.3	0.4	0.0	Feb	14.2	0.4	0.0
Mar	57.1	-0.1	-0.1	Mar	15.4	0.1	0.1	Mar	15.4	0.1	0.1	Mar	16.3	0.1	0.1
Apr	46.5	0.7	-0.7	Apr	20.2	-0.3	0.4	Apr	20.2	-0.3	0.4	Apr	20.4	-0.3	0.4
May	39.2	1.7	-0.1	May	26.4	-0.9	0.0	May	26.4	-1.0	0.0	May	26.0	-0.9	0.0

Jun	25.3	-0.2	-0.2	Jun	29.0	0.1	0.1	Jun	29.0	0.2	0.1	Jun	27.9	0.2	0.2
Jul	22.6	-0.4	-1.0	Jul	30.9	0.2	0.5	Jul	30.9	0.2	0.5	Jul	29.7	0.2	0.6
Aug	47.5	2.6	-0.3	Aug	31.2	-1.0	0.1	Aug	31.2	-1.1	0.1	Aug	30.3	-1.0	0.1
Sep	54.0	-0.6	-0.7	Sep	28.7	0.2	0.2	Sep	28.7	0.3	0.2	Sep	27.6	0.3	0.2
Oct	74.4	-0.9	-0.3	Oct	23.2	0.3	0.0	Oct	23.2	0.3	0.0	Oct	22.7	0.3	0.0
Nov	60.4	-1.0	-0.3	Nov	15.5	0.3	0.0	Nov	15.5	0.4	0.0	Nov	16.2	0.3	0.1
Dec	66.4	-1.9	-0.8	Dec	11.9	0.5	0.2	Dec	11.9	0.6	0.2	Dec	12.9	0.6	0.2

A5-6 Case Study House 3-Bedroom 1

W2CH				W2CH				W2CH				W2CH			
RH%				**Air Temperature°C**				**Radiant Temperature°C**				**Operative Temperature°C**			
Time	Bench Mark	Design-Builder	WUFI Plus	Time	Bench Mark	Design-Builder	WUFI Plus	Time	Bench Mark	Design-Builder	WUFI Plus	Time	Bench Mark	Design-Builder	WUFI Plus
Jan	65.3	-2.1	-0.2	Jan	12.8	-0.6	0.1	Jan	13.9	-0.2	0.1	Jan	13.3	-0.2	0.1
Feb	56.5	-1.8	-0.1	Feb	14.1	0.1	0.0	Feb	15.1	0.7	0.0	Feb	14.6	0.7	0.0
Mar	53.5	-2.1	-0.2	Mar	16.0	-1.6	0.0	Mar	17.2	-1.3	0.0	Mar	16.6	-1.4	0.0
Apr	46.0	-1.0	0.0	Apr	19.6	0.2	0.1	Apr	20.5	0.5	0.1	Apr	20.0	0.4	0.1
May	32.3	0.0	-0.1	May	26.1	0.6	0.0	May	26.3	-0.1	0.0	May	26.2	0.0	0.0
Jun	34.0	0.0	-0.3	Jun	27.6	-0.9	0.0	Jun	27.8	-0.1	0.0	Jun	27.7	0.0	0.0
Jul	36.6	0.3	-0.3	Jul	29.5	-0.6	0.2	Jul	29.5	-0.2	0.2	Jul	29.5	-0.2	0.2
Aug	35.2	0.7	-0.2	Aug	30.7	0.2	0.0	Aug	30.6	-0.4	0.0	Aug	30.7	-0.4	0.0
Sep	49.9	-0.5	-0.5	Sep	27.9	-0.6	0.1	Sep	28.0	0.2	0.1	Sep	28.0	0.2	0.1
Oct	44.6	-1.2	-0.1	Oct	24.7	-0.6	0.0	Oct	24.8	0.4	0.0	Oct	24.8	0.4	0.0
Nov	60.8	-2.1	0.1	Nov	17.3	-0.9	0.0	Nov	18.1	0.8	0.0	Nov	17.7	0.8	0.0
Dec	70.8	-2.6	-0.2	Dec	12.4	-0.6	0.1	Dec	13.6	-0.1	0.1	Dec	13.0	-0.1	0.1

W8LS				W8LS				W8LS				W8LS			
RH%				**Air Temperature°C**				**Radiant Temperature°C**				**Operative Temperature°C**			
Time	Bench Mark	Design-Builder	WUFI Plus	Time	Bench Mark	Design-Builder	WUFI Plus	Time	Bench Mark	Design-Builder	WUFI Plus	Time	Bench Mark	Design-Builder	WUFI Plus
Jan	65.3	-5.1	-0.4	Jan	12.8	0.7	0.1	Jan	13.9	1.3	0.1	Jan	13.3	1.0	0.1
Feb	56.5	-4.2	-0.2	Feb	14.1	1.1	0.1	Feb	15.1	1.9	0.1	Feb	14.6	1.7	0.1
Mar	53.5	-5.5	-0.4	Mar	16.0	1.3	0.1	Mar	17.2	1.8	0.1	Mar	16.6	1.3	0.1

Apr	46.0	-2.6	-1.1	Apr	19.6	1.0	0.5	Apr	20.5	1.4	0.5	Apr	20.0	1.2	0.5
May	32.3	-0.3	-0.3	May	26.1	0.8	0.1	May	26.3	0.1	0.1	May	26.2	0.1	0.1
Jun	34.0	-0.1	-0.3	Jun	27.6	-0.8	0.2	Jun	27.8	0.0	0.2	Jun	27.7	0.0	0.2
Jul	36.6	0.6	-1.1	Jul	29.5	-0.8	0.5	Jul	29.5	-0.3	0.5	Jul	29.5	-0.3	0.6
Aug	35.2	1.5	-0.4	Aug	30.7	-0.1	0.2	Aug	30.6	-0.7	0.2	Aug	30.7	-0.7	0.2
Sep	49.9	-0.7	-0.6	Sep	27.9	-0.6	0.2	Sep	28.0	0.3	0.2	Sep	28.0	0.3	0.2
Oct	44.6	-2.8	-0.2	Oct	24.7	0.0	0.0	Oct	24.8	1.1	0.0	Oct	24.8	1.0	0.0
Nov	60.8	-4.4	-0.2	Nov	17.3	0.1	0.0	Nov	18.1	1.9	0.0	Nov	17.7	1.8	0.0
Dec	70.8	-5.7	-0.7	Dec	12.4	0.6	0.1	Dec	13.6	1.2	0.1	Dec	13.0	1.0	0.2

W8MB				W8MB				W8MB				W8MB			
RH%				**Air Temperature°C**				**Radiant Temperature°C**				**Operative Temperature°C**			
Time	Bench Mark	Design-Builder	WUFI Plus	Time	Bench Mark	Design-Builder	WUFI Plus	Time	Bench Mark	Design-Builder	WUFI Plus	Time	Bench Mark	Design-Builder	WUFI Plus
Jan	65.3	-4.9	-0.5	Jan	12.8	0.6	0.1	Jan	13.9	1.1	0.1	Jan	13.3	1.0	0.1
Feb	56.5	-4.1	0.1	Feb	14.1	1.0	0.0	Feb	15.1	1.8	0.0	Feb	14.6	1.7	0.0
Mar	53.5	-5.3	-0.1	Mar	16.0	1.0	0.1	Mar	17.2	1.5	0.1	Mar	16.6	1.3	0.1
Apr	46.0	-2.5	-0.7	Apr	19.6	0.9	0.4	Apr	20.5	1.3	0.4	Apr	20.0	1.2	0.4
May	32.3	-0.3	-0.1	May	26.1	0.8	0.0	May	26.3	0.1	0.0	May	26.2	0.1	0.0
Jun	34.0	-0.1	-0.2	Jun	27.6	-0.8	0.1	Jun	27.8	0.0	0.1	Jun	27.7	0.0	0.2
Jul	36.6	0.6	-1.0	Jul	29.5	-0.7	0.5	Jul	29.5	-0.3	0.5	Jul	29.5	-0.3	0.6
Aug	35.2	1.4	-0.3	Aug	30.7	-0.1	0.1	Aug	30.6	-0.7	0.1	Aug	30.7	-0.7	0.1
Sep	49.9	-0.8	-0.7	Sep	27.9	-0.6	0.2	Sep	28.0	0.3	0.2	Sep	28.0	0.3	0.2
Oct	44.6	-2.7	-0.3	Oct	24.7	-0.1	0.0	Oct	24.8	1.0	0.0	Oct	24.8	1.0	0.0
Nov	60.8	-4.3	-0.3	Nov	17.3	0.0	0.0	Nov	18.1	1.8	0.0	Nov	17.7	1.8	0.1
Dec	70.8	-5.5	-0.8	Dec	12.4	0.5	0.2	Dec	13.6	1.1	0.2	Dec	13.0	1.0	0.2

A5-7 Case Study House 3-Longe

W2CH				W2CH				W2CH				W2CH			
RH%				**Air Temperature°C**				**Radiant Temperature°C**				**Operative Temperature°C**			
Time	Bench Mark	Design-Builder	WUFI Plus	Time	Bench Mark	Design-Builder	WUFI Plus	Time	Bench Mark	Design-Builder	WUFI Plus	Time	Bench Mark	Design-Builder	WUFI Plus
Jan	65.3	-0.5	0.4	Jan	12.8	0.1	0.0	Jan	13.9	0.1	0.0	Jan	13.3	0.1	0.0

Feb	56.5	-0.1	0.7
Mar	53.5	0.5	0.6
Apr	46.0	0.8	0.9
May	32.3	1.5	0.6
Jun	34.0	1.8	0.7
Jul	36.6	2.2	0.5
Aug	35.2	2.9	0.6
Sep	49.9	1.2	0.0
Oct	44.6	0.7	0.0
Nov	60.8	-0.6	-0.2
Dec	70.8	-1.0	-0.4

Feb	14.1	0.1	-0.1
Mar	16.0	-0.2	-0.1
Apr	19.6	-0.3	-0.2
May	26.1	-0.8	-0.3
Jun	27.6	-0.7	-0.3
Jul	29.5	-0.8	-0.2
Aug	30.7	-1.0	-0.3
Sep	27.9	-0.5	-0.1
Oct	24.7	-0.2	-0.1
Nov	17.3	0.2	0.0
Dec	12.4	0.3	0.1

Feb	15.1	0.1	-0.1
Mar	17.2	-0.2	-0.1
Apr	20.5	-0.4	-0.3
May	26.3	-0.8	-0.3
Jun	27.8	-0.8	-0.4
Jul	29.5	-0.9	-0.3
Aug	30.6	-1.1	-0.3
Sep	28.0	-0.5	-0.1
Oct	24.8	-0.3	-0.1
Nov	18.1	0.2	0.0
Dec	13.6	0.3	0.1

Feb	14.6	0.1	-0.1
Mar	16.6	-0.2	-0.1
Apr	20.0	-0.4	-0.3
May	26.2	-0.8	-0.3
Jun	27.7	-0.8	-0.3
Jul	29.5	-0.9	-0.3
Aug	30.7	-1.1	-0.3
Sep	28.0	-0.5	-0.1
Oct	24.8	-0.3	-0.1
Nov	17.7	0.2	0.0
Dec	13.0	0.3	0.1

W8LS			
RH%			
Time	Bench Mark	Design-Builder	WUFI Plus
Jan	65.3	-0.6	0.8
Feb	56.5	0.4	0.6
Mar	53.5	2.0	0.6
Apr	46.0	2.5	1.0
May	32.3	4.0	0.7
Jun	34.0	4.8	1.2
Jul	36.6	6.1	1.1
Aug	35.2	7.1	0.9
Sep	49.9	4.4	0.7
Oct	44.6	2.9	0.4
Nov	60.8	0.5	0.2
Dec	70.8	-0.6	0.0

W8LS			
Air Temperature°C			
Time	Bench Mark	Design-Builder	WUFI Plus
Jan	12.8	0.2	-0.1
Feb	14.1	-0.1	-0.1
Mar	16.0	-0.8	-0.2
Apr	19.6	-0.9	-0.3
May	26.1	-1.9	-0.4
Jun	27.6	-1.9	-0.6
Jul	29.5	-2.1	-0.5
Aug	30.7	-2.5	-0.4
Sep	27.9	-1.8	-0.3
Oct	24.7	-0.9	-0.2
Nov	17.3	-0.2	-0.1
Dec	12.4	0.2	0.0

W8LS			
Radiant Temperature°C			
Time	Bench Mark	Design-Builder	WUFI Plus
Jan	13.9	0.2	-0.1
Feb	15.1	-0.1	-0.2
Mar	17.2	-0.9	-0.2
Apr	20.5	-1.0	-0.4
May	26.3	-2.0	-0.4
Jun	27.8	-2.1	-0.7
Jul	29.5	-2.3	-0.6
Aug	30.6	-2.7	-0.5
Sep	28.0	-1.9	-0.3
Oct	24.8	-1.0	-0.2
Nov	18.1	-0.2	-0.1
Dec	13.6	0.2	0.0

W8LS			
Operative Temperature°C			
Time	Bench Mark	Design-Builder	WUFI Plus
Jan	13.3	0.2	-0.1
Feb	14.6	-0.1	-0.1
Mar	16.6	-0.8	-0.2
Apr	20.0	-1.0	-0.4
May	26.2	-2.0	-0.4
Jun	27.7	-2.0	-0.6
Jul	29.5	-2.2	-0.5
Aug	30.7	-2.6	-0.5
Sep	28.0	-1.8	-0.3
Oct	24.8	-1.0	-0.2
Nov	17.7	-0.2	-0.1
Dec	13.0	0.2	0.0

W8MB			
RH%			
Time	Bench Mark	Design-Builder	WUFI Plus
Jan	65.3	-0.6	0.7
Feb	56.5	0.3	1.0

W8MB			
Air Temperature°C			
Time	Bench Mark	Design-Builder	WUFI Plus
Jan	12.8	0.2	-0.1
Feb	14.1	-0.1	-0.2

W8MB			
Radiant Temperature°C			
Time	Bench Mark	Design-Builder	WUFI Plus
Jan	13.9	0.2	-0.1
Feb	15.1	-0.1	-0.2

W8MB			
Operative Temperature°C			
Time	Bench Mark	Design-Builder	WUFI Plus
Jan	13.3	0.2	-0.1
Feb	14.6	-0.1	-0.2

Mar	53.5	1.9	1.0	Mar	16.0	-0.8	-0.2	Mar	17.2	-0.8	-0.3	Mar	16.6	-0.8	-0.3
Apr	46.0	2.4	1.4	Apr	19.6	-0.9	-0.4	Apr	20.5	-1.0	-0.5	Apr	20.0	-0.9	-0.4
May	32.3	3.8	1.0	May	26.1	-1.8	-0.4	May	26.3	-2.0	-0.5	May	26.2	-1.9	-0.5
Jun	34.0	4.6	1.3	Jun	27.6	-1.8	-0.6	Jun	27.8	-2.0	-0.7	Jun	27.7	-1.9	-0.6
Jul	36.6	5.7	1.1	Jul	29.5	-2.0	-0.5	Jul	29.5	-2.2	-0.6	Jul	29.5	-2.1	-0.5
Aug	35.2	6.7	1.0	Aug	30.7	-2.4	-0.5	Aug	30.6	-2.6	-0.6	Aug	30.7	-2.5	-0.5
Sep	49.9	4.0	0.6	Sep	27.9	-1.6	-0.3	Sep	28.0	-1.8	-0.3	Sep	28.0	-1.7	-0.3
Oct	44.6	2.6	0.3	Oct	24.7	-0.8	-0.2	Oct	24.8	-0.9	-0.2	Oct	24.8	-0.9	-0.2
Nov	60.8	0.3	0.1	Nov	17.3	-0.1	0.0	Nov	18.1	-0.1	-0.1	Nov	17.7	-0.1	-0.1
Dec	70.8	-0.8	-0.2	Dec	12.4	0.2	0.0	Dec	13.6	0.2	0.0	Dec	13.0	0.2	0.0

A6- Eithc Approval Application for the Case Study Houses Survey

EC1901.409

WELSH SCHOOL OF ARCHITECTURE
ETHICS APPROVAL FORM FOR STUDENT PROJECTS

WSA

Tick one box:	☐ UNDERGRADUATE ☑ M.ARCH ☐ MASTERS
Title of project:	Monitoring the performance of modern and traditional houses of Libya
Name of student(s):	Mohamed Ogali
Name of supervisor:	Eshrar Latif
Contact e-mail address:	Ogalimo@cardiff.ac.uk
Date:	22/01/2019

Participants		YES	NO	N/A
Does the research involve participants from any of the following groups?	• Children (under 16 years of age)			✓
	• People with learning difficulties			✓
	• Patients (NHS approval is required)			✓
	• People in custody		✓	✓
	• People engaged in illegal activities		✓	
	• Vulnerable elderly people			✓
	• Any other vulnerable group not listed here			✓
• When working with children: I have read the Interim Guidance for Researchers Working with Children and Young People (http://www.cardiff.ac.uk/archi/ethics_committee.php)		✓		

Consent Procedure	YES	NO	N/A
• Will you describe the research process to participants in advance, so that they are informed about what to expect?	✓		
• Will you tell participants that their participation is voluntary?	✓		
• Will you tell participants that they may withdraw from the research at any time and for any reason?	✓		
• Will you obtain valid consent from participants? (specify how consent will be obtained in Box A)[1]	✓		
• Will you give participants the option of omitting questions they do not want to answer?	✓		
• If the research is observational, will you ask participants for their consent to being observed?	✓		
• If the research involves photography or other audio-visual recording, will you ask participants for their consent to being photographed / recorded and for its use/publication?	✓		

Possible Harm to Participants	YES	NO	N/A
• Is there any realistic risk of any participants experiencing either physical or psychological distress or discomfort?		✓	
• Is there any realistic risk of any participants experience a detriment to their interests as a result of participation?		✓	

Data Protection		YES	NO	N/A
• Will any non-anonymous and/or personalised data be generated or stored?			✓	
• If the research involves non-anonymous and/or personalised data, will you:	• gain written consent from the participants	✓		
	• allow the participants the option of anonymity for all or part of the information they provide	✓		

Health and Safety	YES
Does the research meet the requirements of the University's Health & Safety policies? (http://www.cf.ac.uk/osheu/index.html)	✓

Research Governance	YES	NO	N/A
Does your study include the use of a drug? You need to contact Research Governance before submission (resgov@cf.ac.uk)		✓	
Does the study involve the collection or use of human tissue? You need to contact the Human Tissue Act team before submission (hta@cf.ac.uk)		✓	

[1] If any non-anonymous and/or personalised data be generated or stored, *written consent* is required.

Prevent Duty	YES	
Has due regard be given to the 'Prevent duty', in particular to prevent anyone being drawn into terrorism? https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/445916/Prevent_Duty_Guidance_For_Higher_Education__England__Wales_.pdf http://www.cardiff.ac.uk/publicinformation/policies-and-procedures/freedom-of-speech	✓	

If any of the shaded boxes have been ticked, you must explain in Box A how the ethical issues are addressed. If none of the boxes have been ticked, you must still provide the following information. The list of ethical issues on this form is not exhaustive; if you are aware of any other ethical issues you need to make the SREC aware of them.

Box A The Project (provide all the information listed below in a separate attachment)

1. Title of Project
2. Purpose of the project and its academic rationale
3. Brief description of methods and measurements
4. Participants: recruitment methods, number, age, gender, exclusion/inclusion criteria
5. Consent and participation information arrangements - please attached consent forms if they are to be used
6. A clear and concise statement of the ethical considerations raised by the project and how is dealt with them
7. Estimated start date and duration of project

All information must be submitted along with this form to the School Research Ethics Committee for consideration

Supervisor's declaration (tick as appropriate)	
• I consider this research project to have **negligible ethical implications** and **the student can proceed with the research immediately** (*can only be used if none of the grey areas of the checklist have been ticked*).	✓
• I consider this project research to have **some ethical implications. Box A** clearly describes the ethical issues and how they are addressed. **The student has to await feedback whether the research has been approved by the SREC Chair or whether it will have to be considered by the Committee**. The student will receive feedback within 7-10 days.	
• I consider this project to have **significant ethical implications** and should be brought before the Ethics Committee. **Box A** clearly describes the ethical issues and how they are addressed. **The student MUST NOT proceed until the project has been approved by the Ethics Committee.**	

Signature [signature] Name **Eshrar Latif** Date 29.01.19

Advice from the School Research Ethics Committee

- Keep the data for 5 years after completion.
- Add Supervisor's email address to the consent form.
- Summarise the project purpose on the consent form.

STATEMENT OF ETHICAL APPROVAL

This project had been considered using agreed Departmental procedures and is now approved

Signature pp K Lewis   Name Research Manager for ~~Ethics~~ Chair following her email   Date 31/1/19

Chair, School Research Ethics Committee

1. **Title of the project:** Part of my research which will be to monitor the thermal performance of the traditional and modern Libyan houses.
2. **Purpose of the project:** to get real time data on the weather conditions and the thermal performance of the houses.
3. **Methods and measurements:** to monitor the temperature, air movement and relative humidity levels.
4. **Recruitment methods:** selecting some case study houses in different regions of Libya (coast, desert and mountains) with agreement with the owners of the houses.
5. **Estimate starting dates**: will be in two seasons (summer and winter) and will last for approximately 30 days each season.

Consent Form - Confidential data

I understand that my participation in this project will involve [*...permission to monitor the thermal performance of the house...*].

I understand that participation in this study is entirely voluntary and that I can withdraw from the study at any time without giving a reason.

I understand that I am free to ask any questions at any time. I am free to withdraw or discuss my concerns with [*Eshrar Latif*].

I understand that the information provided by me will be held confidentially, such that only the Principal Investigator and [name(s) of other researchers where applicable] can trace this information back to me individually. The information will be retained for up to [state amount of time data will be held] when it will be deleted/destroyed.

plan is to keep the data permanently.

I understand that I can ask for the information I provide to be deleted/destroyed at any time and, in accordance with the Data Protection Act, I can have access to the information at any time.

I, ___________________________________ **[PRINT NAME]** consent to participate in the study conducted by [*Mohamed Dgali*], Welsh School of Architecture, Cardiff University with the supervision of [*name of supervisor*].

Signed:

Date:

1

A7- Thermal Comfort, Occupants Behaviour and Energy Use Survey

Evaluating the Performance of Traditional and Contemporary Domestic Buildings in the Mediterranean region

This questionnaire contains thirty question, divided into four sections. Each of the sections contains several questions that are designed as an approach to the objectives of this research. Section one is the "House Design Details", consist of sixteen question that deals with the details of the houses. At the conclusion, different house types with different areas, different construction materials in addition to other aspects were chosen and will be used as an input for simulation.

Section two, is the "Energy Use in the Libyan houses". This section contains three questions (Q 17-Q 20). This section is dealing with the energy performance and energy use in the Libyan houses. At the end of this section, an estimations of energy consumption, cost and a rule of thumb calculations of heating and cooling loads of the Libyan houses.

Section three is the "Adaptive behaviour and thermal comfort measurements". This section consists of six questions (Q.21- Q.26). this section is trying to identify the actions that people do, to feel thermally comfortable, prior to switching on the mechanical equipment. Also, this section measures the thermal comfort degree in the different regions of Libya. At the conclusion, it seems that people in the different regions of Libya have showed different approaches to thermal comfort, but mostly, people are using the mechanical equipment without taking any other passive actions. In terms of the thermal comfort degree, the survey revealed different temperatures in which people feel thermally comfortable in both seasons, winter and summer.

Section four, is the last section and is to be answered by specialists in the construction industry only. This section contains three questions (Q.27- Q.30). in this section, specialists were asked to state their opinion regarding the architecture of Libya (both modern and traditional).

The detailed analysis of the survey is presented here, starting with section one "House Design Details" (Pages: 2-31).

1. *Section one "House Design Details" (questions 2-16)*

This section contains sixteen questions, that are dealing with the characterisation of the houses, in terms of location (region), type, area, number of floors, number of the occupants, age of the house, envelope details (thickness and construction materials of the walls and roof, in addition to the locations, size and number of windows in each facade) and building orientation.

Q.1. the city you live in (Region)?

Based on several factors, such as climate and geography, a variety of authors divided Libya into three regions [176]. Those regions are; Coast, Mountain, and Desert. Fig.1.

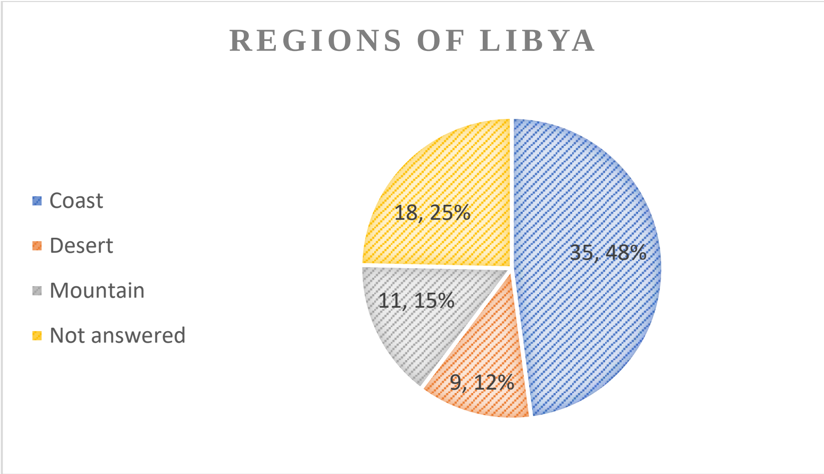


Fig.1. regions of Libya

In the figure above, it can be seen that thirty-five houses, 48% of the total answers, are located in the Coast region, eleven houses, 15% of the total answers, are in the Mountain region, and nine houses are from the Desert region, which is 12% of the total answers. Eighteen houses chose not to answer, which is 25% of the total answers.

Q.2.The type of houses you live in?

The literature revealed that there are five house types, those are: Villa, Flat, Detached and Semi-detached house, and the traditional Courtyard house Fig.2.

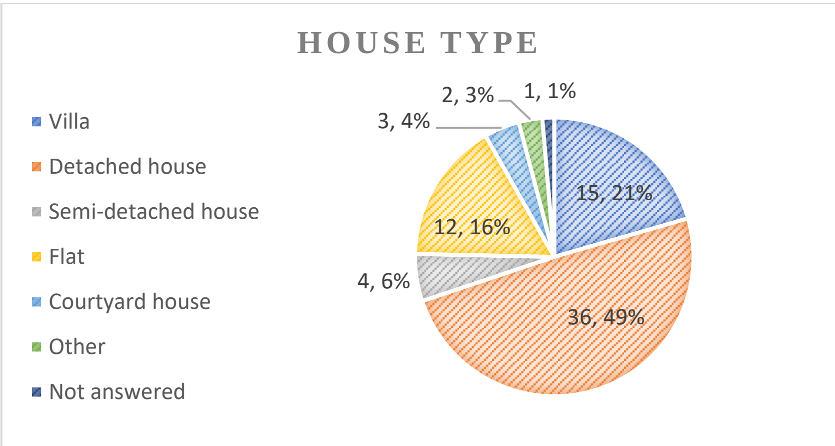


Fig.2. Common house types

The figure shows that the most common house type is the Detached house, with thirty-six votes, which is 49% of the total answers, followed by Villa by 21%, and fifteen votes, Flat comes third with twelve votes, which is 16% of the total surveyed houses. four answered that they live in Semi-detached houses which is 6% of the total answers. Three houses, 4% of the total, are courtyard house, two choose other, and only one choose not to answer. Table.1 shows the type and number of houses in each region.

Table.1. Type and number of houses for each region

Region	Villa	Flat	Detached house	Semi-Detached house	Courtyard house	Other	*Total (Region)*
Coast	10	6	16	2	1	-	*35*
Desert	1	-	6	1	-	1	*9*
Mountain	1	3	7	-	-	-	*11*

Not answered	2	3	7	1	2	1	*16*
Total (Type)	*14*	*12*	*36*	*4*	*3*	*2*	71

Q.3. How many floors in the house?

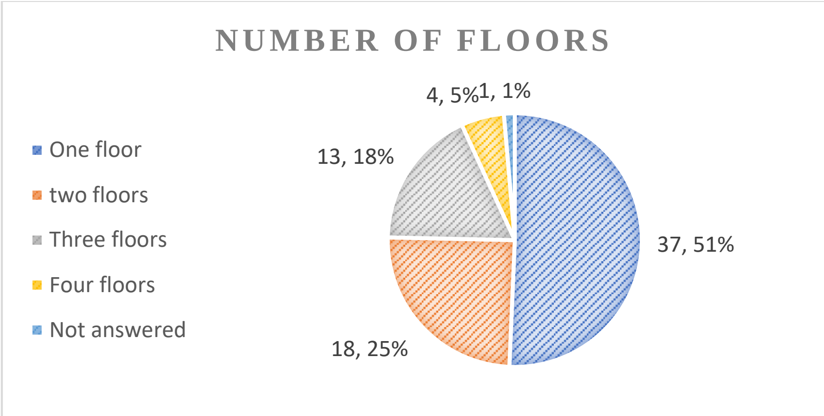


Fig.3. Number of floors in the house

The results indicate that most of the houses are single storey houses with thirty-seven votes, which is %51 of the total sample, eighteen are two-storey houses, which is %25 of the total house, thirteen are three stories, which represent a %18 of the total sample, and four answered that they live in four-story houses, %5 of the total houses.

The number of floors for each house type, and in each region, is showed in details in Table.2.

Q.4.What is the approximate area (square meter) of each floor?

For the different house types indicated earlier (Villa, Flat, Detached house, Semi-detached house and Courtyard house), different areas were given. Those areas are showed in the following figures (Fig.4,5,and 6).

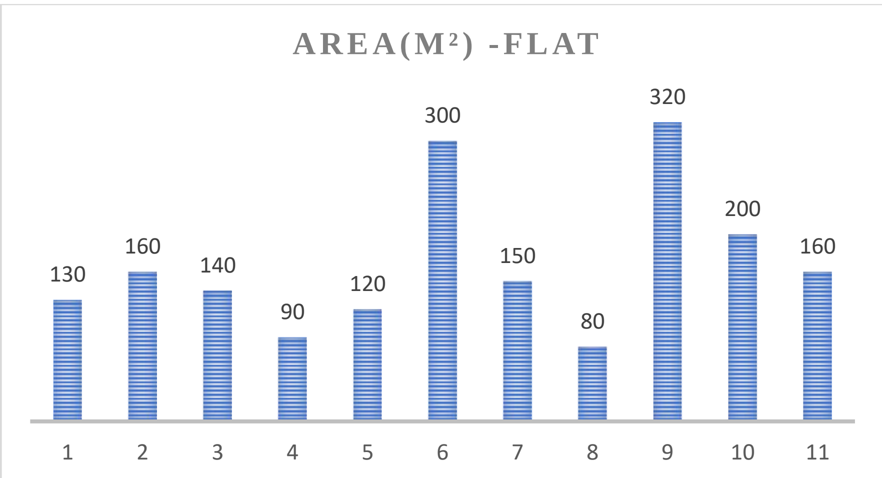


Fig.4. Different floor areas for flat.

For Flats, different floor areas are found, and are ranging from 80m² to 320m².The average area (m²) per person for flat can be found in Table.2.

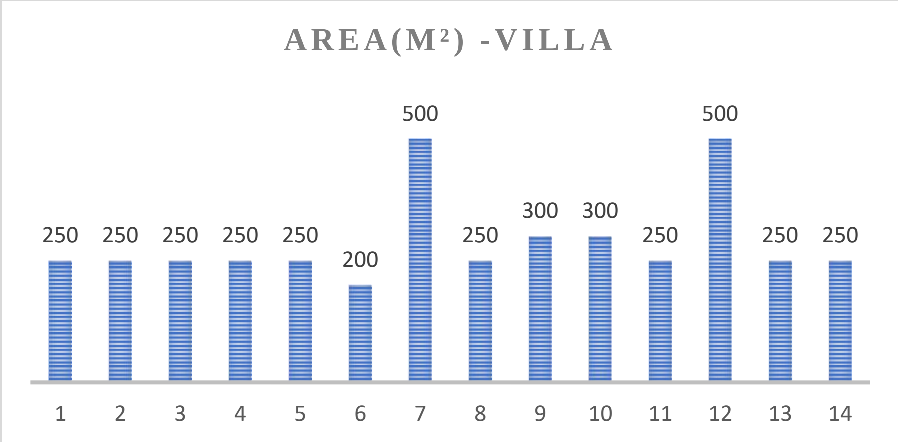


Fig.5. Different floor areas for Villa.

For Villa, the results also showed different floor areas. The area ranges for the Villa are from 200m² to 1000m² as showed in the figure above. Table.2. shows detailed floor area for Villa and the average floor area per person.

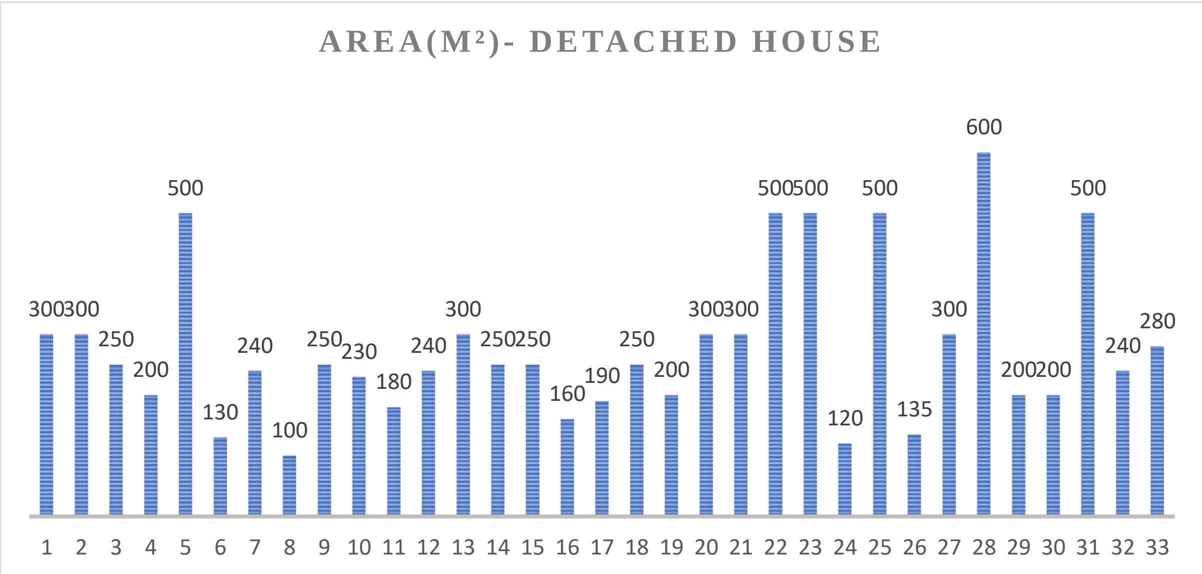


Fig.6. Different floor areas for detached houses

The results of the survey showed that detached house is the most common house type in Libya, and the figure above shows that there are different floor areas for detached house ranging from 100m² to 1000m². More details on floor areas of detached houses can be found in Table.2. below.

Q.5. How many people living in the house?

According to [177] the Libyan population is 6,754,507 as of July 2017 -July 2017 estimates. With a total area land of 1,759,540 km² that is mostly desert or semi desert (about 90% of the land is desert).

The Average household for each type in each region, are showed in table.2. below. The following formula is used to calculate the average area (m²) per person for each house type. (Area per person **(m²) =Total area / Total number of occupants)**

Table.2. Area per person for each house.

Type	Region	N.O. floors	Area (m²)	N.O. of residents	Area per person (m²)
Villa	Coast	2	250	8	62.5
		2	250	8	62.5
		3	700	9	233.3
		1	250	4	62.5
		1	250	4	85.7
		2	200	5	125
		2	1000	5	400
		2	500	8	125
		1	300	8	80
		2	300	7	400
		2	250	4	125
	Desert	2	500	8	125
	Mountain	1	300	8	37.5
	Not answered	1	250	4	62.5

Average floor area=710.7m², STDEV=618.6m², Average per person=141.9m²,STDEV= 119.6 m²

Type	Region	N.O. floors	Area (m²)	N.O. of residents	Area per person (m²)
Flat	Coast	N/A	160	4	40
		N/A	300	5	60
		N/A	200	7	28.5
	Mountain	N/A	140	8	17.5
		N/A	90	3	30
	Desert	N/A	320	10	32

Average floor area=201.6m², STDEV=91.3m², Average per person=34.6m²,STDEV= 14.4 m²

Type	Region	N.O. floors	Area (m²)	N.O. of residents	Area per person (m²)
Detached house	Coast	1	300	9	33.3
		1	300	4	75
		3	500	6	250
		4	130	17	30.6
		1	100	2	50
		2	240	7	68.6
		1	230	7	32.9
		1	180	7	25.7
		1	200	4	50
		1	200	9	22.2
		1	250	7	35.7
		1	250	5	50
		3	300	7	128.6
		1	190	5	38
		1	280	9	31.1

Average floor area=392m², STDEV=363.6m², Average per person=61.4m², STDEV= 58.7m²

	Mountain	2	200	5	80
		2	500	8	125
		2	160	4	80
		1	200	5	40
		1	120	5	24

Average floor area=408m², STDEV=348m², Average per person=69.8m², STDEV= 39.5m²

	Desert	1	240	4	60
		1	250	3	83.3
		1	250	4	62.5
		1	300	5	60
		2	500	6	166.7
		1	600	7	85.7

Average floor area=440m², STDEV=307m², Average per person=86.3m², STDEV= 41m²

	Not answered	1	240	11	21.8
		2	300	10	60
		1	250	7	35.7
		1	135	5	27
		2	300	8	75
		1	500	6	83.3

Average floor area=387.5m², STDEV=203.6m², Average per person=50.5m², STDEV= 25.9m²

Type	**Region**	**N.O. floors**	**Area (m²)**	**N.O. of residents**	**Area per person (m²)**
Semi-detached	Coast	2	200	6	66.7
		3	170	7	72.9
	Mountain				
	Desert	1	230	7	32.9
	Not answered	2	200	10	40

Type	**Region**	**N.O. floors**	**Area(m²)**	**N.O. of residents**	**Area per person (m²)**
Courtyard house	Coast	3	150	15	30
		1	190	9	21.1
	Desert	1	40	10	4
		3	200	14	42.9

Q.6. When was the house built?

To indicate the age of the house, and the approximate time of when the house was built. The results are showed in Fig.7.

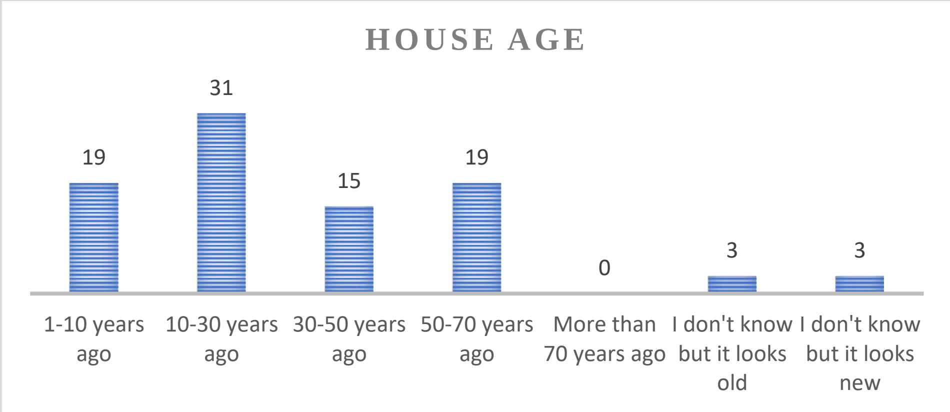


Fig.7. Age of the house

From the figure above, it can be seen that nineteen answered that they live in new houses that are1-10 years' old, thirty-one answered 10-30 years old, fifteen answers are 30-50 years old, and nineteen of the participants answered that they live in houses that are 50-70 years old, while three answered that their houses look new and three answered that they live in a house that looks old.

Q.7. What is the thickness of the main external walls?

Different thicknesses for the external walls are used, and the ranges are 15cm to 50cm depending on the construction material and the construction technique used. The results are showed in Fig.8. below.

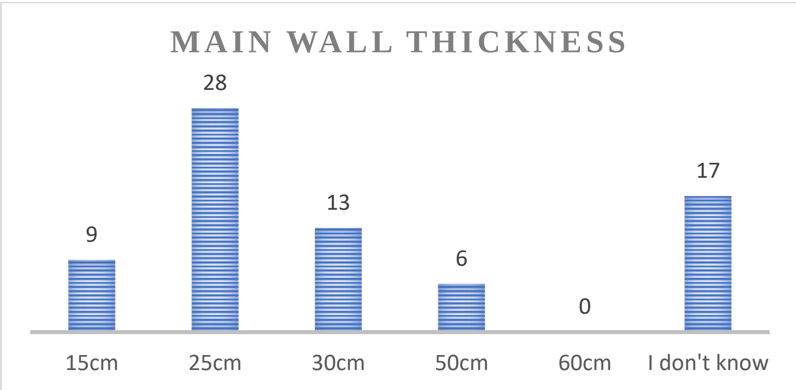


Fig.8. thickness of the main external walls

The figure shows that nine houses have main external walls that are 15cm thick, twenty-eight houses have external walls with 25cm thickness, thirteen houses have 30cm thick walls, six are 50cm thick, and seventeen answered that they do not know the thickness of the external walls of their houses. The result also showed that in some cases, despite using the same construction material, walls can have different thicknesses. Table.3. shows in detail the different construction materials and the thickness of the walls and roofs of the modern Libyan houses.

Q.8. What are the construction materials of the main external walls (You may choose more than one answer)?

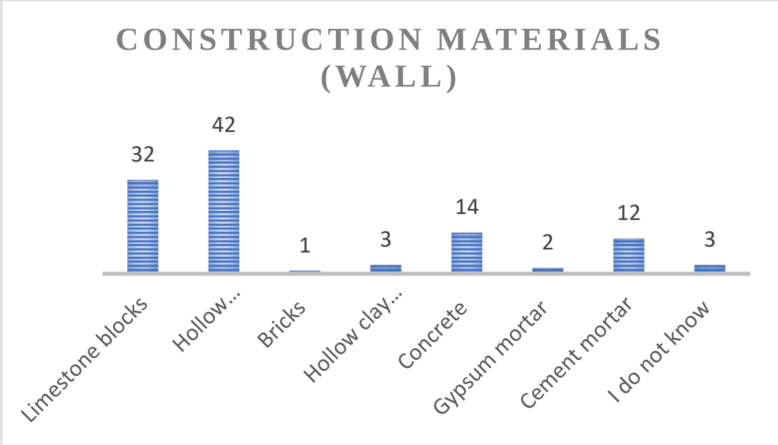


Fig.9. construction materials of the external walls

The figure above shows that the dominant construction material for the external walls is Hollow concrete blocks with forty-two votes, followed by limestones with thirty-two votes, concrete fourteen votes, and Hollow clay blocks with three votes. The figure also shows that twelve houses use cement mortar and only two voted for Gypsum mortar.

Q.9. What is the thickness of the roof of the upper floor (or the ceiling in case you live in a flat)

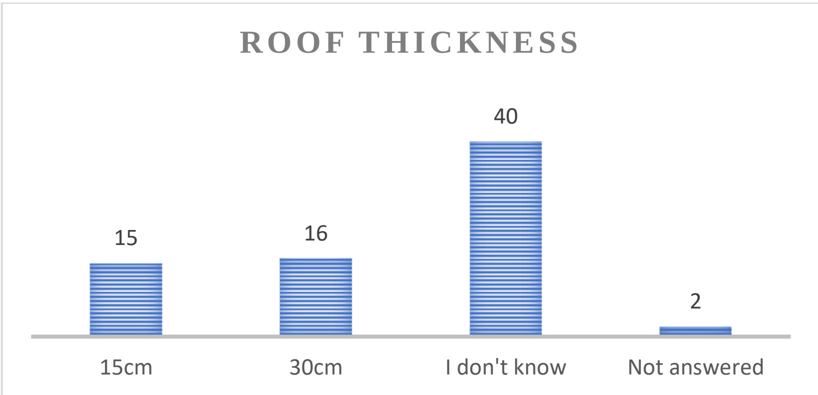


Fig.10. roof thickness

As can be seen in the figure above, the thickness of the roofs varies depending on the construction materials used. The figure shows that fifteen houses have roofs that are 15cm thick, sixteen answered that the thickness of their roofs is 30cm.

Q.10. What are the construction materials of the roof of the upper floor (or the ceiling in case you live in a flat)

In this question, participants were asked to identify the construction materials used in the roofs of their houses. The answers are shown in Fig.11. below.

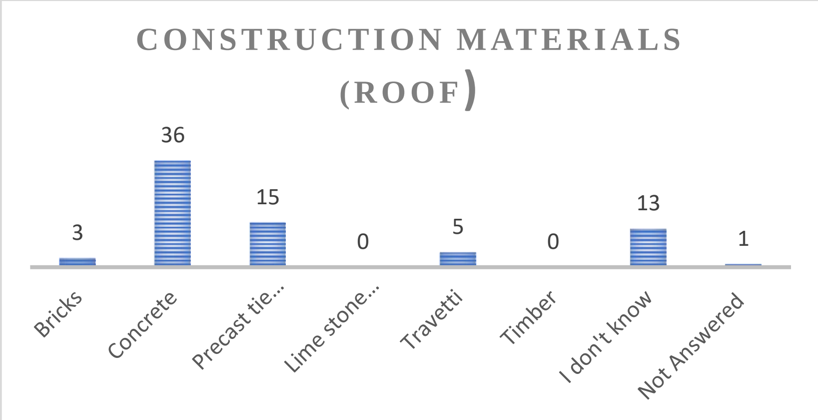


Fig.11. roof's construction materials

the figure above shows that the dominant construction material of the roofs of the modern Libyan houses is concrete with thirty-six votes, precast tie beams come second with fifteen votes, followed by Travetti with five votes and brick with three votes. Thirteen answered they do not know the construction materials of the roofs of their houses. Table.3. below contains a detailed breakdown of the envelope of different houses in the different regions of Libya.

Table.3. envelope details for different house types in the different regions of Libya

Type	Region	Thickness (wall)(cm)	Construction materials (Wall)	Thickness (roof)(cm)	Construction materials (Roof)
Villa	Coast	-	limestones	-	-
		-	limestones	-	-
		-	Hollow concrete blocks	-	Concrete
		25	Hollow concrete blocks	-	Precast tie beams
		25	Hollow concrete blocks, Limestone blocks	30	Travetti
		50	Limestone blocks	30	-
		-	Hollow concrete blocks	-	Concrete
		-	Hollow concrete blocks	-	Concrete
		25	Limestone blocks, Cement mortar	30	Precast tie beams
		-	Hollow concrete blocks	-	-
	Desert	15	Hollow concrete blocks	-	Precast tie beams
	Mountain	30	Hollow concrete blocks	-	Precast tie beams
	Not mentioned	50	Limestone blocks, Concrete, Hollow clay blocks, Cement mortar	-	Precast tie beams
		-	Hollow concrete blocks	-	-

Type	Region	Thickness (wall)(cm)	Construction materials (Wall)	Thickness (roof)(cm)	Construction materials (Roof)
Flat	Coast	25	Hollow concrete blocks	-	Concrete
		50	Limestone blocks	-	Concrete
		15	Hollow concrete blocks	15	Concrete
		30	-	-	Concrete
		25	Hollow concrete blocks	15	Concrete

		25	Hollow concrete blocks, Cement mortar	15	Concrete
	Mountain	-	Hollow concrete blocks	-	Concrete
		25	Hollow concrete blocks, Limestone blocks	15	Concrete
		25	Limestone blocks, Cement mortar	30	Concrete
	Not answered	15	-	15	Concrete
		30	Hollow concrete blocks	-	-
		30	Hollow concrete blocks, Limestone blocks	30	Travetti

Type	**Region**	**Thickness (wall)(cm)**	**Construction materials (Wall)**	**Thickness (roof)(cm)**	**Construction materials (Roof)**
Detached house `	Coast	30	Hollow concrete blocks+ Limestone blocks	-	-
		-	Hollow concrete blocks	-	Concrete
		-	Hollow concrete blocks, Limestone blocks	-	Travetti
		25	Hollow concrete blocks	30	Precast tie beams
		50	Limestone blocks, Cement mortar	-	Concrete
		25	Limestone blocks	-	Bricks
		50	Limestone blocks	-	Precast tie beams
		25	Hollow concrete blocks	15	Precast tie beams
		25	Hollow concrete blocks	30	Precast tie beams
		25	Hollow concrete blocks	30	Concrete
		25	Limestone blocks	30	Concrete
		30	Hollow concrete blocks	-	Concrete
		-	Hollow concrete blocks	-	Concrete
		30	Limestone blocks	30	Precast tie beams
		25	Hollow concrete blocks, Limestone blocks, concrete, Cement mortar	30	Precast tie beams
		25	Limestone blocks	15	Concrete
	Mountain	25	Limestone blocks	15	Concrete
		25	Bricks	-	Travetti
		-	Limestone blocks	-	-
		-	Limestone blocks	-	-
		30	Limestone blocks	-	Concrete
		25	Hollow concrete blocks, Gypsum mortar	30	Precast tie beams
		25	Limestone blocks	15	Concrete
		-	Limestone blocks	-	Concrete
	Desert	15	-		Concrete
		25	Hollow concrete blocks	-	-
		15	Hollow concrete blocks	15	Bricks
		30	Limestone blocks, Cement mortar	-	Concrete
		25	Hollow concrete blocks	15	Concrete
	Not answered	25	Hollow concrete blocks	30	-
		15	Limestone blocks	15	Concrete
		25	Limestone blocks	-	Precast tie beams
		25	Hollow concrete blocks	15	Concrete
		15	Limestone blocks	30	Precast tie beams

		15	Hollow concrete blocks	15	Bricks
		30	Limestone blocks, concrete, Cement mortar	-	Concrete

Type	Region	Thickness (wall)(cm)	Construction materials (Wall)	Thickness (roof)(cm)	Construction materials (Roof)
Semi-detached house	Coast	15	Hollow concrete blocks	-	-
		25	Hollow concrete blocks	-	Concrete
	Desert	30	Hollow concrete blocks, Cement mortar	15cm	Concrete
	Not answered	25	Hollow concrete blocks+ Limestone blocks	15	Concrete

Type	Region	Thickness (wall)(cm)	Construction materials (Wall)	Thickness (roof)(cm)	Construction materials (Roof)
Courtyard house	Coast	-	Limestone blocks, Cement mortar	-	Concrete
		-	-	-	-
		25cm	Limestone blocks	-	Concrete

Type	Region	Thickness (wall)(cm)	Construction materials (Wall)	Thickness (roof)(cm)	Construction materials (Roof)
Other	Desert	25	Hollow concrete blocks	30	-
		30	Hollow concrete blocks	-	Concrete

1. Building envelope details for each region

From Table.3. above, a detailed analysis of the building envelope for each region is presented here in form of figures.

a. Wall's construction materials

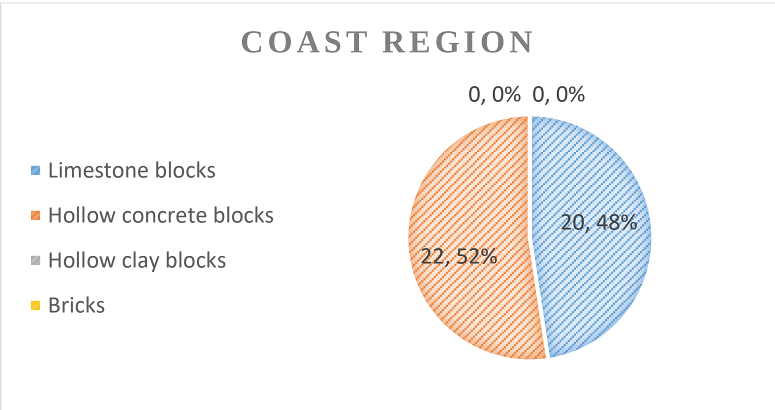


Fig.12. Wall's construction materials (Coastal region)

Fig.12. show that the dominant construction material of walls in the Coast region is Hollow concrete block by twenty-two votes which is 40%, followed by Limestone by 36% and twenty votes.

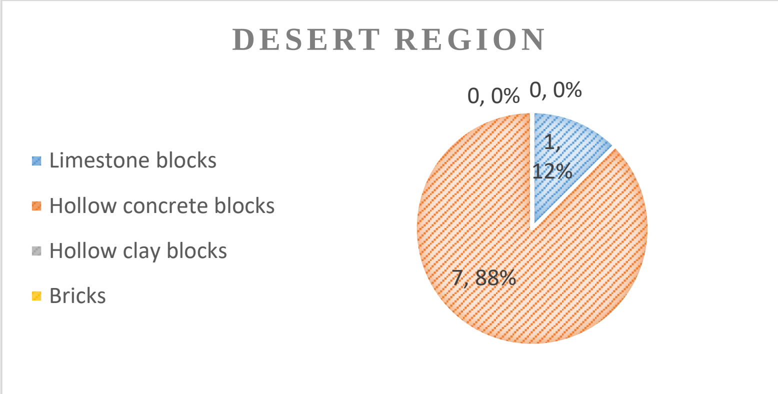


Fig.13. Wall's construction materials (Desert region)

For the Desert region, the results showed that 54% of the walls are constructed with Hollow concrete block, 23% are concrete walls and 8% using Limestones.

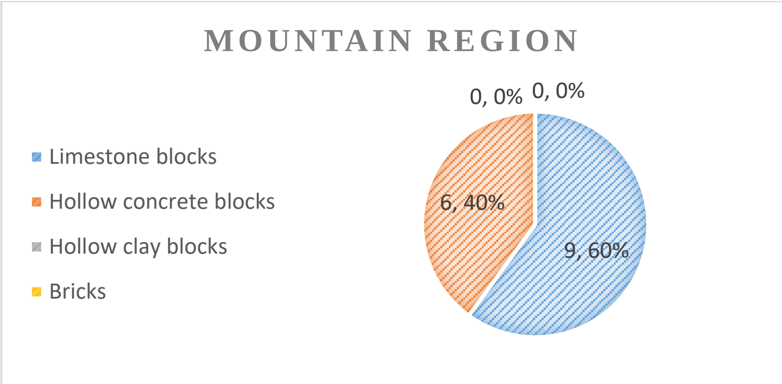


Fig.14. Wall's construction materials (Mountain region)

Form the Figure above, in the mountain region, the dominant construction material for walls is Limestone by 47%, followed by Hollow concrete blocks by 32%.

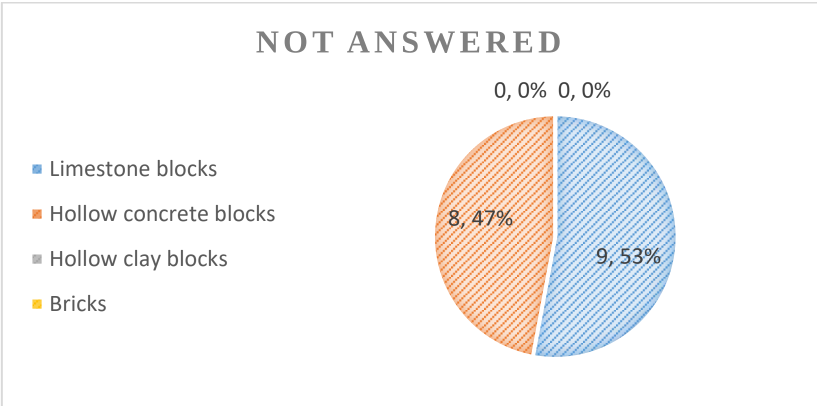


Fig.15. Wall's construction materials (not answered)

For participants that chose not answer their region, 47% answered that the construction materials used in the walls of their houses is Hollow concrete blocks, while the remaining 53% are made of Limestone blocks.

b. Roof construction materials

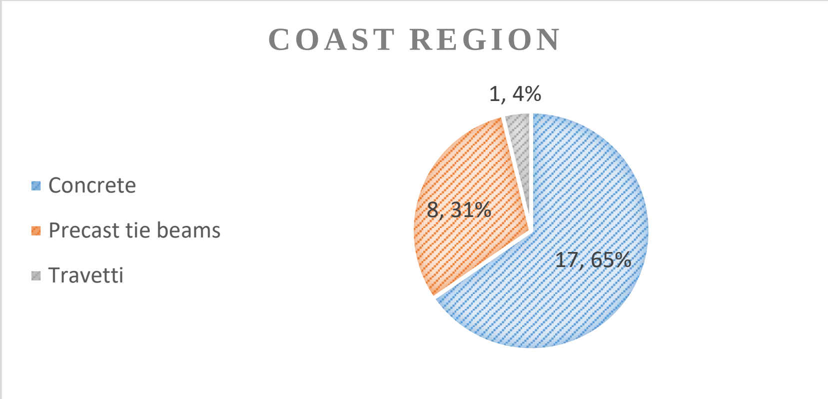


Fig.16. Roof's construction materials (Coastal region)

Figure .16. above Indicate that the dominant construction materials of the roofs in the Coastal region are 65% concrete, 31% Precast tie beams and only 4% Travetti.

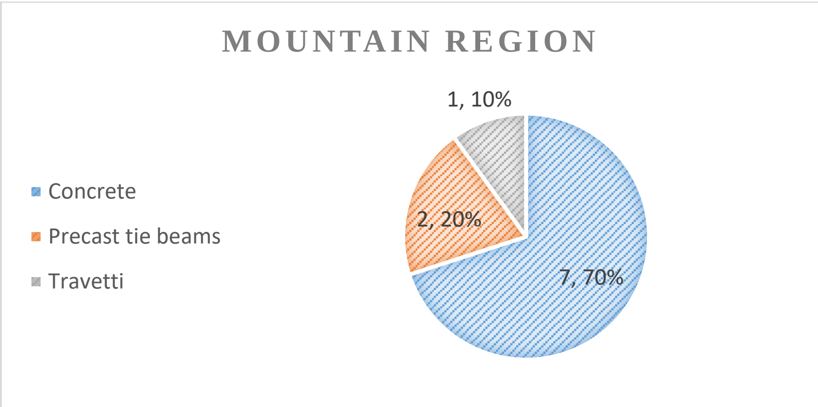


Fig.17. Roof's construction materials (Mountain region)

The figure above shows that the construction material of walls in the mountain region is mainly concrete by 70%, Precast tie beams was voted second by 20% and only 10% voted for Travetti.

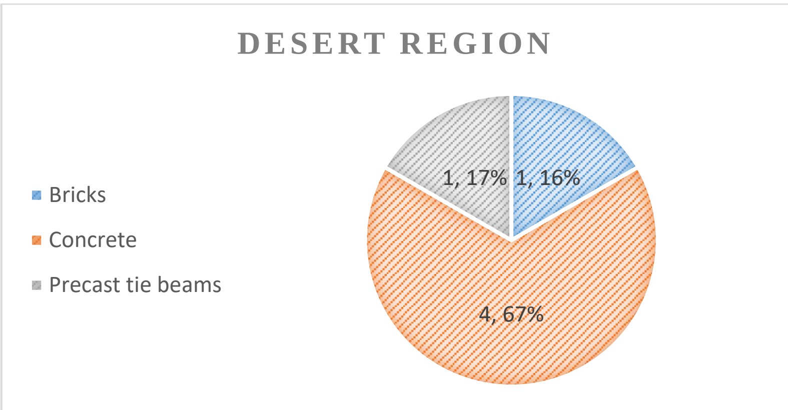


Fig.18. Roof's construction materials (Desert region)

In the Desert region, 67% voted for Concrete as the main construction materials for roofs, and both Bricks and Pre tie beams have 17%, as can be seen in Fig.18.

Table.4. below list and shows the number of walls and roof with their thickness and construction materials.

Table.4. Different materials and thickness for walls and roofs

Wall material	Thickness (cm)					Roof material	Thickness (cm)	
	15	20	25	30	50		15	30
Hollow clay blocks	-	-	-	-	-	Concrete	13	3
Hollow concrete blocks	4	-	17	6	-	Precast tie beams	1	7
Limestone blocks	2	-	8	4	3	Bricks	2	-
Brick	-	-	1	-	-	Travetti	-	2
Total (thickness)	8	-	26	11	3	Total (roofs)	16	12

As can be seen in the table above, there are eight walls that are 15cm thick and uses two different construction materials, those materials are Hollow concrete blocks, and Limestone blocks. The table also shows that there are twenty-six walls that are 25cm thick, and the materials used are Hollow concrete blocks, Limestones and Bricks. The tables also shows that there are eleven walls that are 30cm thick, and the material used is Hollow concrete and Limestone blocks. Finally, the table shows that there are three walls that are 50cm thick and the material used is Limestone blocks.

For roofs, the table shows two main thicknesses, 15cm and 30cm. sixteen roofs are 15cm thick, and the materials are Precast tie beams, Concrete, and Bricks. Twelve roofs are of 30cm thickness, and the materials used are Precast tie beams, Concrete, and Travetti.

Q.11. If your house contains a courtyard, what is the size of the courtyard?

Courtyards with different sizes are found in the traditional houses of Libya. The studies showed that in the Mountain region, the courtyard size is 10m*10m (Large) [176], while in the Coast region, the courtyard's size was reported to be 6.5m*5.0m (Medium) [176] and in the Desert region, the courtyard size is 4.7m*4.0m (Small) [176]. The results are shown in Fig.19.

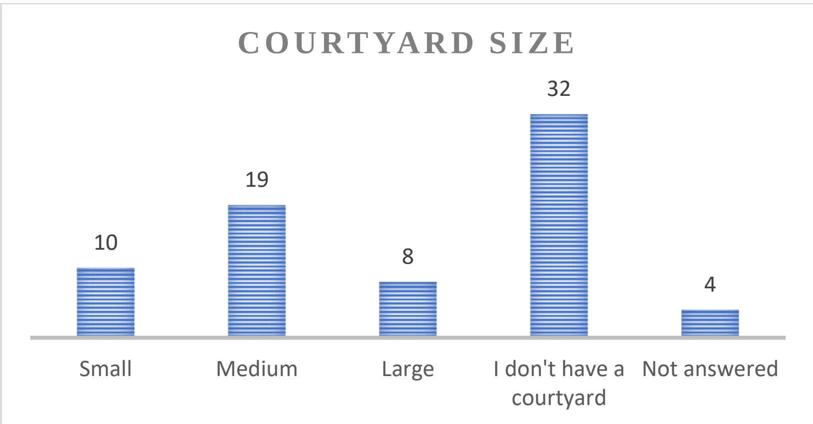


Fig.19. Courtyard size.

Thirty-two voted that they do not have a courtyard, eight voted they have a large courtyard, nineteen answered that they have a medium sized courtyard, and ten answered that their houses contain a small courtyard.

Q.12. What is the orientation of the main facade?

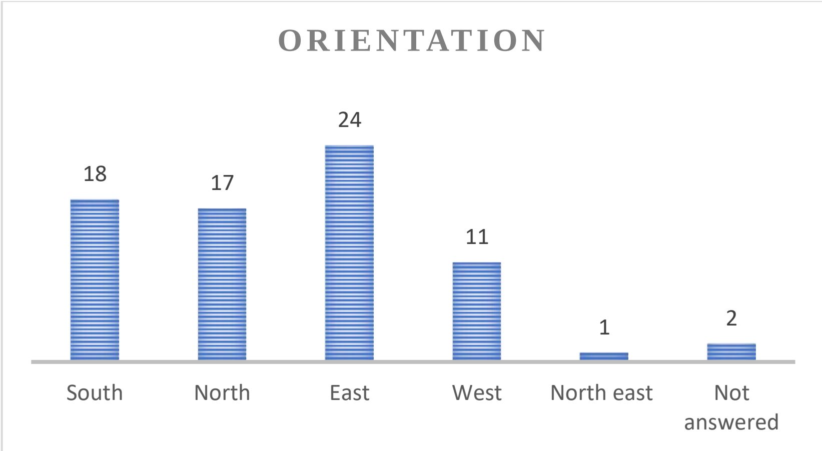


Fig.20. main facade orientation.

The figure showed that in the three regions of Libya, different and random orientations are used. The figure also shows that East orientation was the most common among the houses of all regions with twenty-four votes, South, and North orientations follow with eighteen and seventeen votes respectively, while eleven houses are West-oriented.

Detailed orientation for each house can be found in Table.5. and the detailed orientation for each region are showed in the figures 21, 22, and 23.

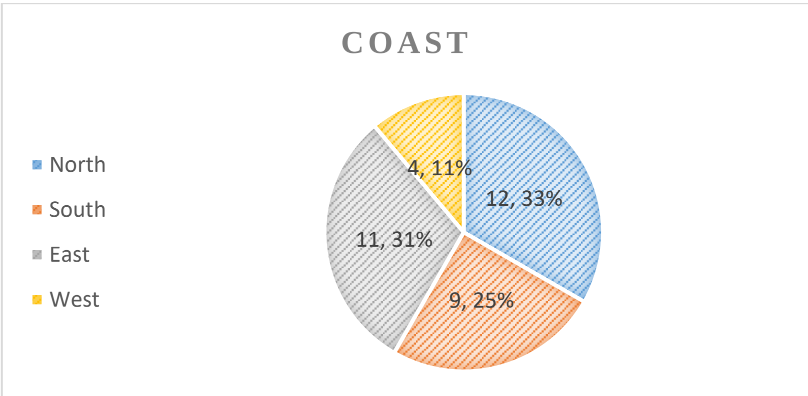


Fig.21. Different houses orientations (Coast region)

From the figure above, houses in the Coast region have different and random orientations.

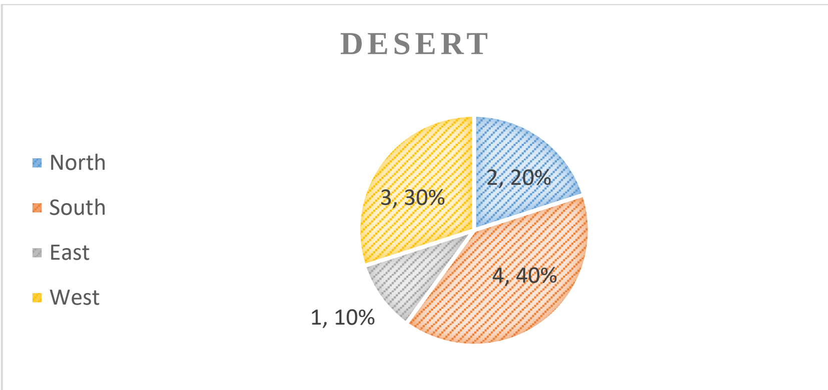


Fig.22. Different houses orientations (Desert region)

For the Desert region, the figure above shows South and West orientation are the most common. East and North orientations are also found.

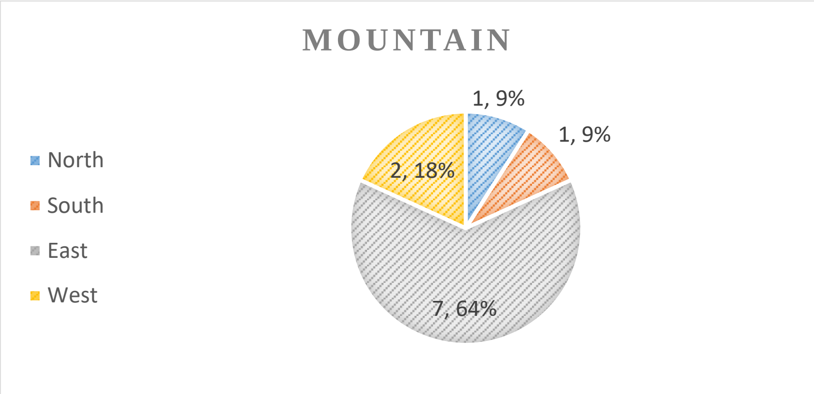


Fig.23. Different houses orientations (Mountain region)

In the Mountain region, the results show that houses are mostly East oriented.

Table.5. below shows in detail, the building orientation, courtyard size, and windows details.

Table.5. Building orientation, courtyard size, windows size, number and location.

Type	Region	Orientation	Courtyard size (m²)			Location/Number of windows	
			S	M	L	Main facade	Rear facade /Courtyard
Villa	Coast	North				6	6
		North				6	6
		North			100	-	-
		West		32.5		8	4
		East				6	-
		East				18	2
		North				-	-
		South			100	5	5
		East		32.5		3	4
		West				3	10
	Desert	East				9	2
	Mountain	East				3	-
	Not answered	South				-	7
Type	**Region**	**Orientation**	**Courtyard size (m²)**			**Location/Number of windows**	
			S	**M**	**L**	**Main facade**	**Rear facade /Courtyard**
Flat	Coast	South				2	6
		East				2	0
		North				5	-
		North				-	-
		East		32.5		-	-
		North east				2	2
	Mountain	West				1	2
		East				3	2
		North				0	0
	Not answered	North				4	1
		North		32.5		-	-
		East			100	8	27
Type	**Region**	**Orientation**	**Courtyard size (m²)**			**Location/Number of windows**	
			S	**M**	**L**	**Main facade**	**Rear facade /Courtyard**

Detached house	Coast	East	18.8			3	2
		East		32.5		4	4
		South		32.5		12	8
		North	18.8			12	1
		West	18.8			3	3
		South		32.5		2	3
		West		32.5		8	8
		South				0	3
		South		32.5		3	4
		East	18.8			3	-
		South				2	2
		East	18.8			4	2
		North				6	7
		North			100	2	3
		South				5	5
		East		32.5		2	4
	Mountain	East	-			2	4
		East	-			-	-
		South	-			2	-
		East		32.5		-	2
		West	-			3	4
		East	-			4	3
		East	-			2	3
	Desert	North	18.8			4	4
		South	-			4	3
		West		32.5		1	3
		South	-			-	3
		South			100	8	26
		North	-			2	4
Type	**Region**	**Orientation**	**Courtyard size (m²)**			**Location/Number of windows**	
			S	**M**	**L**	**Main facade**	**Rear facade /Courtyard**
Semi-detached house	Coast	North	18.8			8	3
		South	-			4	3
	Desert	South		32.5		1	10
	Not answered	West		32.5		2	3
Type	**Region**	**Orientation**	**Courtyard size(m²)**			**Location/Number of windows**	
			S	**M**	**L**	**Main facade**	**Rear facade /Courtyard**
Courtyard house	Coast	North	18.8			17	3
		East		32.5		-	-
		North	-			2	3
Type	**Region**	**Orientation**	**Courtyard size (m²)**			**Location/Number of windows**	
			S	**M**	**L**	**Main facade**	**Rear facade /Courtyard**
Other	Desert	West	-			2	4
		West	18.8			-	9

Q.14. What is the average size of windows on each floor?

In this question, participants were asked to state the size of the windows of each floor of their houses. The answers are showed in figures 24,25, and 26 and Table.5. above shows a detailed window sizes for different house types in the different regions of Libya.

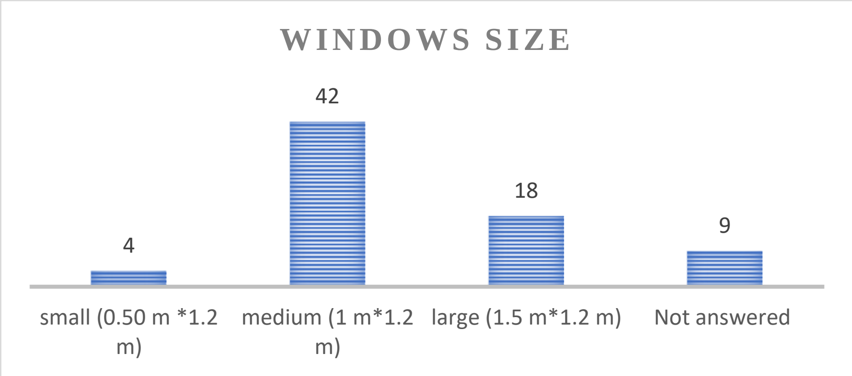


Fig.24. windows size (Ground floor)

In the ground floor, the figure shows different window sizes, but mostly medium sized windows (around 1m*1.2m), and in some cases large windows (around 1.5m*1.2) as can be seen in the figure above.

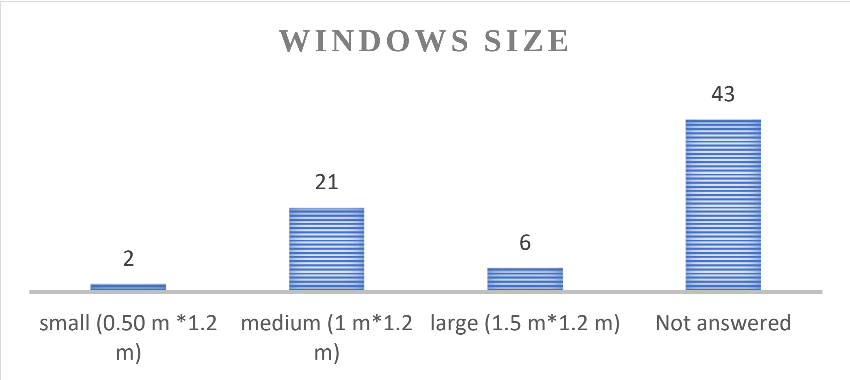


Fig.25. windows size (Upper floor)

In the cases of multiple floors, twenty one houses answered that they have medium sized window (around 1m*1.2m) in the upper floor, six answered that they have large windows in the upper floor (around 1.5m*1.2m), and two stated that their houses contain small windows in the upper floor (around 0.5m*1.2m)

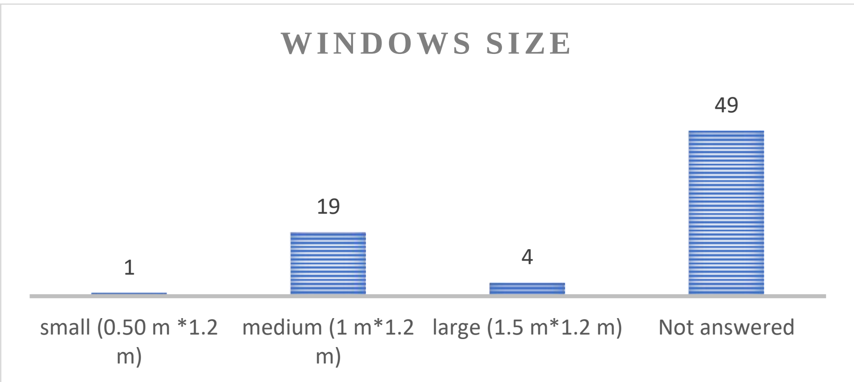


Fig.26. windows size (Flat)

For flats, nineteen answered that their windows are medium sized (around 1m*1.2m), four answered that the windows in their flats are of large size (around 1.5m*1.2m) and one flat has small windows (around 0.5m*1.2m).

Q.15. How many windows in the main facade?

The number and the size of the windows is different for each house and in each region. Tables.6. shows the number and the size of the windows for each house. the table also shows some calculations for window to floor ratio, which will be used later to construct models in Design Builder for simulations, to test the performance of the windows in providing daylight and natural ventilation. To calculate the WFR, the following formula is used:

WFR (%) = total area of the window/total floor area of the house*100

The results for each house are shown in the Table below.

Table.6. Window to floor ratio

Type	Region	Area (m^2)	Window area(m^2)			N.O. window /floor	N.O floors	Total windows area(m^2)	WFR%
			S	M	L				
Villa	Coast	250		1.2		20	2	48	9.6
		250		1.2		20	2	48	9.6
		700			1.5	25	3	112.5	5.3
		250		1.2		8	1	9.6	3.84
		300			1.5	7	2	21	3.5
		250		1.2		20	2	48	9.6
		500		1.2		4	3	14.4	0.96
		200		1.2		15	2	36	9
		1000			1.5	13	2	39	1.95
	Desert	500			1.5	35	2	105	10.5
	Not answered	250			1.5	7	3	31.5	4.2
		250		1.2		4	1	4.8	1.92
Type	**Region**	**Area** (m^2)	**Window area(m^2)**			**N.O. window /floor**	**N.O floors**	**Total windows area(m^2)**	**WFR%**
			S	M	L				
Flat	Coast	160		1.2		8	N/A	9.6	6
		159		1.2		3	N/A	3.6	2.25
		120		1.2		9	N/A	10.8	9
		300		1.2		7	N/A	8.4	2.8
		150		1.2		4	N/A	4.8	4.2
		200		1.2		7	N/A	8.4	3.2
	Mountain	140		1.2		8	N/A	9.6	6.85
		90		1.2		6	N/A		8
	Not answered	130		1.2		8		9.6	7.38
		80		1.2		6		7.2	9
		320		1.2		31		37.2	11.6
Type	**Region**	**Area** (m^2)	**Window area(m^2)**			**N.O. window /floor**	**N.O floors**	**Total windows area(m^2)**	**WFR%**
			S	**M**	**L**				
Detached house	Coast	300			1.5	6	1	4.8	1.9
		300		1.2		8	1	9	3
		500		1.2		25	3	9.6	3.2
		130		1.2		4	4	90	6

		100		1.2		4	1	19.2	3.7
		240		1.2		17	2	4.8	4.8
		230		1.2		8	1	40.8	8.5
		180		1.2		10	1	9.6	4.1
		200		1.2		10	1	12	6.6
		200		1.2		6	1	12	6
		250		1.2		10	1	7.2	3.6
		250		1.2		7	1	12	4.8
		300		1.2		25	3	8.4	3.4
		190	1.0			7	1	90	10
		280			1.5	10	1	7	3.7
	Mountain	200		1.2		7	2	16.8	4.2
		160		1.2		7	2	16.8	5.2
		200		1.2		6	1	7.2	3.6
		120			1.5	7	1	10.5	8.7
	Desert	240			1.5	8	1	10.5	8.7
		250			1.5	11	1	12	5
		250		1.2		7	1	16.5	6.6
		500		1.2		34	2	8.4	3.3
		600		1.2		6	1	81.6	8.1
	Not answered	240		1.2		8	1	7.2	1.2
		300		1.2		13	2	9.6	4
		250		1.2		7	1	31.2	5.2
		135		1.2		6	1	8.4	3.3
		300		1.2		27	2	7.2	5.3
		500			1.5	8	1	64.8	10.8
Type	**Region**	**Area (m²)**	**Window area(m²) S**	**M**	**L**	**N.O. window /floor**	**N.O floors**	**Total windows area(m²)**	**WFR%**
Semi-detached house	Coast	200			1.5	13	2	39	9.6
		170	1.0			10	3	30	5.9
	Desert	230			1.5	11	1	16.5	7.2
	Not answered	200		1.2		5	2	12	3
Type	**Region**	**Area (m²)**	**Window area(m²) S**	**M**	**L**	**N.O. window /floor**	**N.O floors**	**Total windows area(m²)**	**WFR%**
Courtyard house	Coast	150		1.2		20	3	72	16
		190		1.2		11	1	13.2	6.9
Type	**Region**	**Area (m²)**	**Window area(m²) S**	**M**	**L**	**N.O. window /floor**	**N.O floors**	**Total windows area(m²)**	**WFR%**
Other	Desert	40		1.2		6	1	7.2	18
		200		1.2		9	3	32.4	5.4

Q.16. How many windows overlooking the courtyard or Back of the building?

The number and position of windows for each house type, are showed in detail in Table.5. above.

Conclusion

The most important findings from the first section (House design details), will be presented here starting with:

i. **Construction materials**

Table.7. The most common construction materials and their usage in % in each region

Region	Wall		Roof	
	Construction materials	**Usage**	**Construction materials**	**Usage**
Coast	Hollow concrete block, Limestone blocks	52% 48%	Concrete Pre tie beams Travetti	65% 31% 4%
Desert	Hollow concrete block	88%	Concrete Pre tie beams	67% 17%
	Limestone	12%	Bricks	16%
Mountain	Limestones Hollow concrete blocks	60% 40%	Concrete Pre tie beams Travetti	70% 20% 10%
Not answered	Limestones	53%		
	Hollow concrete block	47%		

From the table above, in the Cost region, the most used construction material is Hollow concrete blocks and Limestones blocks for wall. As for the roofs, concrete is found to be the most common construction material in the coast region. In the Desert region, the table shows that the dominant construction material for walls is Hollow concrete blocks, and for roofs, concrete is the most common construction material. Finally, the table shows that for the Mountain region, the most used construction materials for wall is Limestones blocks, and for roofs, concrete was found to be the most used construction material. Common wall thickness in each region, is showed in Fig.23. below.

ii. Wall and roof thickness

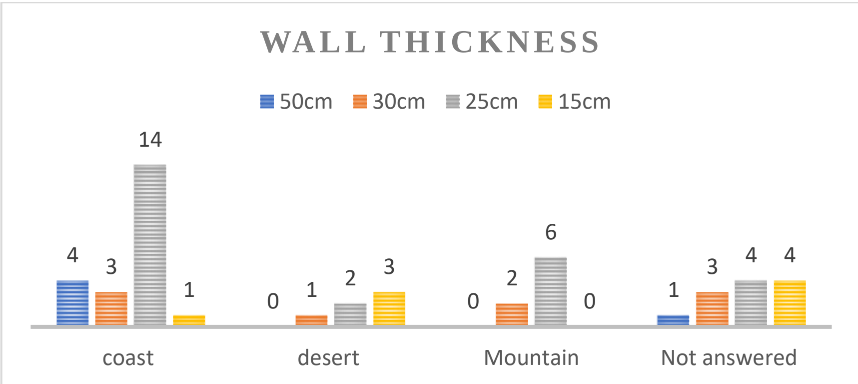


Fig.27. Wall thickness for the different region of Libya

From the figure above, it can be seen that in all regions, different wall types with different thickness are used. The figure shows that the most common wall thickness in the Coast region is 25cm, and in the Desert region, the figure shows that 15cm is the most common wall thickness, and for the Mountain region, the most common thickness is found to be 25cm.

iii. Average building area

The average building area and the average area per person for each house type in each region are showed in Table.8.

Table.8. average house area and average area per person for different house types in the different regions of Libya

Type	Region	Average area(m^2)	STDEV	Average per person (m^2)	STDEV
Villa	All regions	710.7	618.6	141.9	119.6
Flat	All regions	201.6	91.3	34.6	14.4
Detached house	Coast	392	363.6	61.4	58.7
	Mountain	408	348	69.8	39.5
	Desert	440	307	86.3	41

iv. Building orientation

As discussed earlier in Q.16. there was no common orientation and the houses in all the regions are found to be randomly oriented.

v. Window size/Location

Table.9. below shows different wall to floor ratios (WFR) for different house types, in the different regions of Libya.

Table.9. different floor areas and different WFR for different buildings in the different regions of Libya

Type	Region	Average area(m^2)	Average window Area(m^2)	STDEV	Average WFR%	STDEV
Villa	All	710.7	43.15	34.14	5.8	3.6
Flat	All	201.6				
Detached house	Coast	392	22.4	28.8	4.9	2.19
	Mountain	408	12.8	4.8	4.5	2.3
	Desert	440	21.4	21.1	6.34	2.2

2. Section two: Energy Use in the Libyan houses (questions 17-20)

To understand the energy use and energy performance of the Libyan houses. This section contains four main questions (Q.17-Q.20).

Q.17. is to identify type and number of the domestic appliances used in each house. This will help to outline some values and estimations of energy consumption and the cost of using that equipment. In Q.18., participants were asked to state the approximate energy cost (electricity, and gas monthly bill). Q.19. contains three subsections. In each of those sections, participants were asked to estimate: the number of light bulbs in their houses, the daily hours of using the artificial light, the daily hours of using the TV, and the daily hours of using the electrical/gas cooker. Finally, in Q.20. the participants were asked to state the daily hours of using the hot water during winter. The results of this section will give an idea on the energy consumption, use and cost of the Libyan houses.

Q.17. which of the following mechanical equipment you have in your house (you may choose more than one answer)

The answers are showed in Fig.28.

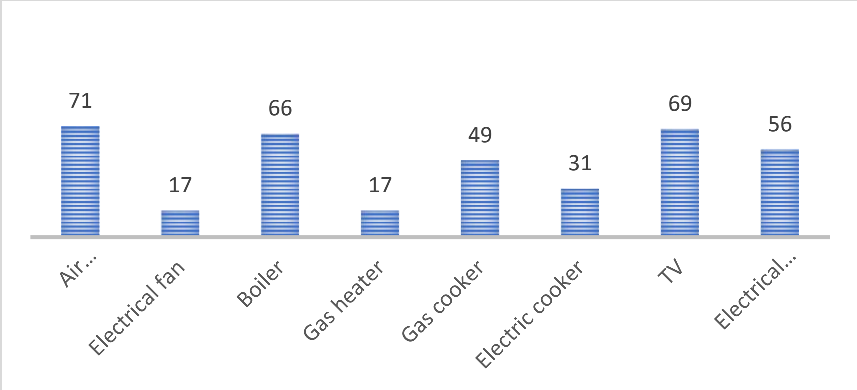


Fig.28. Appliances available in the houses.

From the figure above, most of the houses are using air conditioners with seventy-one votes, followed by TV, sixty-nine votes, Boilers for hot water with sixty-six votes and Gas cooker with forty-nine votes. Table.10. shows the estimated energy consumption and cost for some domestic appliances. The calculations are based on a single device that is used for one hour a day, the capacity of those appliances is based on the estimate available at [178], [179], and [180]. The Cost of energy is calculated based on the cost of energy in Libya which is 0.2 LD/KWh [181]. The following equation is used to calculate the cost of energy,

Watts ÷1000 = kW x hours of operation = kWh x kWh rate = cost

Table.10. Estimated energy cost for some domestic appliances

Type	**Rating (h)**	**Cost (LD)/h**	**Notes**
A/C	14,000 BTU	2.051	On average, a 7kg washing machine use 70 Litres of water per wash.
Electrical fan	75W	0.0375	
Immersion heater	3000W	1.5	
Washing machine	1200-3000W	1.5	
Oven	2000-2200W	1.1	
Fridge-freezer	200-400W	0.2	
Plasma TV	280-450W	0.225	
LCD TV	125-200W	0.1	
Vacuum Cleaner	700-900w	0.45	
Gas heater	350	e	
Gas cooker	5000	e	
Electric cooker	870W	0.435	
Electrical heater	1200W	0.6	
Incandescent bulb	100W	0.05	

Q.18. what is the estimated cost for energy? Please, state the amount below.

Table.11. shows the estimated monthly cost of energy (electricity and gas and any other type of energy) for each house type in the different regions of Libya.

Table.11. Estimated monthly energy cost

Type	**Area(m²)**	**N.O. residents**	**Electricity cost (LD)**	**Gas cost (LD)**
Villa	500	8	80	30
	500	8	80	30

	250	4	70	7
	400	5	150	-
	2000	5	100	-
	600	7	120	14
	500	4	50	-
	300	8	200	-

Average monthly electricity cost = 106.25 LD, average monthly gas cost= 20.25 LD

Type	**Area(m²)**	**N.O. residents**	**Electricity cost (LD)**	**Gas cost (LD)**
Flat	160	4	35	10
	140	8	30	-
	120	5	45	50
	300	5	50	-
	150	6	70	-
	80	4	22	25
	320	10	100	25
	160	9	50	10
	-	5	120	20
	140	8	30	-

Average monthly electricity cost = 55.2 LD, average monthly gas cost= 23.3 LD

Type	**Area(m²)**	**N.O. residents**	**Electricity cost (LD)**	**Gas cost (LD)**
Detached	300	9	55	20
house	300	4	100	-
	240	5	60	5
	100	2	15	2
	250	4	30	3
	230	7	60	10
	180	7	25	-
	240	11	200	50
	300	10	50	10
	250	7	30	5
	250	5	600	-
	160	4	40	10
	190	5	50	10
	250	3	30	4
	200	4	300	10
	900	7	90	25
	-	7	70	20
	1000	6	60	35
	120	5	150	10
	1000	8	-	10
	135	5	-	35
	600	8	30	10
	200	9	10	3
	-	7	-	15
	-	-	100	50
	200	5	100	35
	500	6	-	25
	280	9	50	15

Average monthly electricity cost = 96 LD, average monthly gas cost= 17.8 LD

Type	**Area(m²)**	**N.O. residents**	**Electricity cost (LD)**	**Gas cost (LD)**

Semi-detached house	400	10	25	30
	510	7	90	25
	230	7	140	-

Q.19. Can you estimate the following?

A- Number of light bulbs in the house

The answers are showed in Table.12. below.

Table.12. number of light bulbs in the house

Type	Area(m^2)	N.O. bulbs	Average N.O. bulbs per m^2	Estimated time of use(h)
Villa	500	45	0.09	7-9
	500	45	0.09	7-9
	250	40	0.16	+9
	400	20	0.05	+9
	500	150	0.30	7-9
	1500	20	0.01	+9
	600	300	0.50	7-9
	750	50	0.07	7-9

*Average N.O. bulbs per m^2= **0.158**, STDEV=**0.163**, average time of use= **10.125**, STDEV= **1.55***

Type	Area(m^2)	N.O. bulbs	Average N.O. bulbs per m^2	Estimated time of use(h)
Detached house	300	9	0.03	7-9
	300	50	0.17	7-9
	250	15	0.06	+9
	400	15	0.04	7-9
	1500	100	0.07	4-6
	520	20	0.04	4-6
	240	12	0.05	7-9
	100	10	0.10	4-6
	250	45	0.18	4-6
	230	50	0.22	7-9
	180	25	0.14	7-9
	240	20	0.08	+9
	600	16	0.03	7-9
	250	29	0.12	7-9
	250	7	0.03	7-9
	190	17	0.09	4-6
	250	60	0.24	7-9
	300	15	0.05	4-6
	1000	18	0.02	+9
	120	10	0.08	+9
	1000	20	0.02	+9
	135	11	0.08	7-9
	600	70	0.12	7-9
	600	15	0.03	4-6
	200	20	0.10	7-9
	200	15	0.08	1-3
	500	10	0.02	+9
	480	30	0.06	1-3
	280	30	0.11	7-9

*Average N.O. bulbs per m^2= **0.084**, STDEV=**0.059**, average time of use= **8.48**, STDEV= **2.54***

Type	Area(m^2)	N.O. bulbs	Average N.O. bulbs per m^2	Estimated time of use (h)
Flat	130	32	0.25	4-6
	160	9	0.06	7-9
	140	20	0.14	7-9
	90	6	0.07	7-9
	120	15	0.13	7-9
	300	20	0.07	7-9
	150	22	0.15	7-9
	80	6	0.08	4-6
	320	27	0.08	4-6
	200	17	0.09	7-9
	160	20	0.13	4-6
*Average N.O. bulbs per m^2= **0.11**, STDEV=**0.055**, average time of use= **7.90**, STDEV= **1.51***				

Type	Area(m^2)	N.O. bulbs	Average N.O. bulbs per m^2	Estimated time of use(h)
Semi-detached house	200	20	0.10	7-9
	200	30	0.15	+9
	170	27	0.16	4-6
	230	15	0.07	+9
*Average N.O. bulbs per m^2= **0.12**, STDEV=**0.04**, average time of use= **9**, STDEV= **2.44***				

B. Daily hours of using the TV

The answers are showed in Fig.29. below

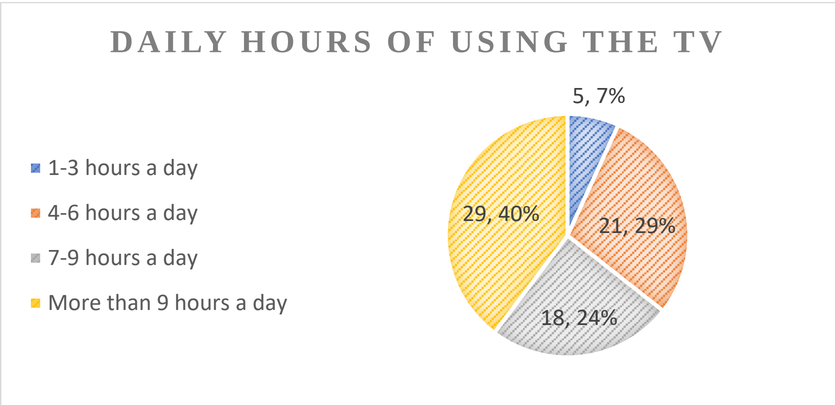


Fig.29. Daily hours of using TV

The figure shows that 40% of the participants are using the TV for more than nine hours a day, 24% are using the TV between seven to nine hours a day, 29% answered four to six hours a day and 7% are using the TV for one to three hours a day.

C. Daily hours of using the electrical/gas cooker

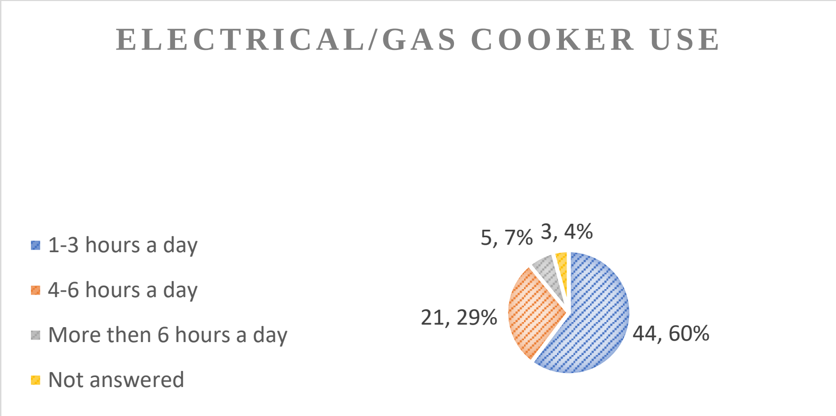


Fig.30. Daily hours of using the electrical/gas cooker

The figure shows that 60% of the participants are using the cooker for one to three hours a day, 29% answered four to six hours and 7% for more than six hours a day.

Q.20. During the winter, on an average, for how many hours hot water is used daily?

Participants were asked to identify the approximate time of using hot water for the different daily activates. The answers were as follow:

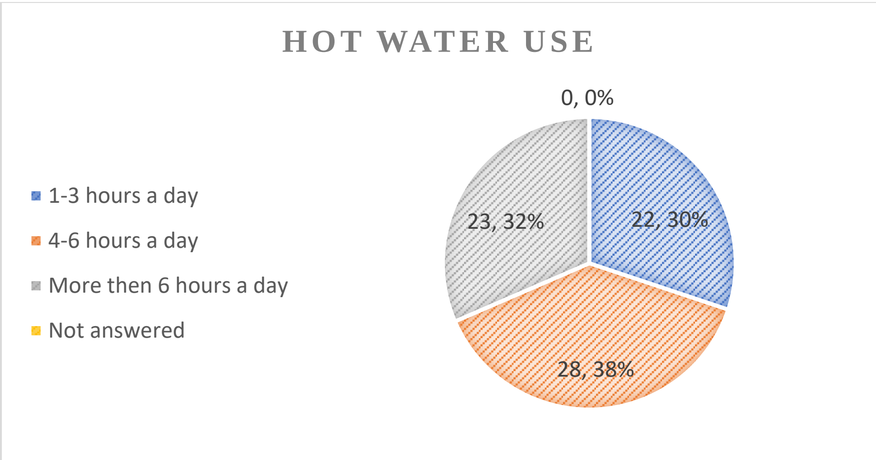


Fig.31. approximate daily hot water use

The answers show that hot water is needed during winter; the average period of using the hot water is, however, different. 30% said that they using hot water for approximately one to three hours, 38% stated that need hot water for four to six hours a day and 32% answered that hot water is needed for more than six hours a day.

a. Conclusion

i. Estimated energy consumption and cost for lighting

Table.13. below contains the estimated energy consumption and energy cost for different house types. The following equations are used for calculations:

- *N.o. of bulbs= Area * N.o. bulbs per m²*
- *Energy consumption = (rating (W)/1,000 (kw)) * N.o. bulbs * operation time*
- *Operation cost= energy consumption * KWh rate*

- *Amount of light produced= (60 w incandescent bulb= 800lm) =800lm*number of bulbs.*

Table.13. estimated energy consumption/cost for lighting in different house types

Type	*Area (m^2)*	*No. of bulbs per m^2*	*No. bulbs (Total)*	*Light produced (Lumens)*	*Time of use (h)*	*Consumption (KWh)*	*Operation cost (LD)*
Villa	710.7	0.158	112	89600	10.125	67.2	2.016
Flat	201.6	0.12	24	19200	9	12.96	0.388
Detached house	411	0.084	35	28000	8.48	17.808	0.534
Semi-Detached house	200	0.12	24	19200	9	12.96	0.388

ii. Estimated energy consumption/cost for some domestic appliances

The following table shows some estimated values for energy consumption and cost.

Table.14. estimated energy consumption and cost for TV, Cooking, and hot water

Device	Average operation time (h)	Rate (KWh)	Estimated energy consumption (KWh)	Estimated cost (LD)
Plasma TV	12	450	4.05	2.7
Electrical cooker	3	870	2.61	1.305
Immersion heater (for hot water)	6	3000	18	9

iii. Cooling load calculations

Basic calculations of the estimated mechanical cooling capacity, and the estimated operation costs for cooling are showed in the table15. Below. The capacity of the mechanical equipment is calculated based on the assumption of 20 BTU/ft² [182]. The energy cost estimate is calculated based on the current electricity price in Libya, which is 0.2 LD/KWh.

Table.15 estimated A/C capacity, average and operation costs of using air conditioning

Type	*Average area*		*Cooling Capacity*		*Estimated cost (LD h)*	*Cost (Average time of use 10.23 h)*
	(m^2)	*ft^2.*	*(BTU h)*	*(KWh)*		
Villa	710.7	7643	152,860	44.8	8.96	91.66
Flat	201.6	2170	43,400	12.7	2.54	25.98
Detached house	413	4445.5	88,910	26.58	5.3	54.38

iv. Space heating requirements calculations

Space heating requirements estimated energy consumption and the energy cost required for heating during winter will be calculated here.

Table.16. shows the average and the extreme temperatures during winter [183]. the estimated energy consumption and the cost of heating during winter are also showed in the table.

The heating factor will be 35-40 BTU per ft². Which is the heating factor for the Csa climate (Hot-summer Mediterranean) [184].

Table.16 estimated A/C capacity, average and operation costs of using air conditioning

Type	*Average are*		*Heating Capacity*		*Estimated cost (LD h)*	*Cost (Average time of use 8 h)*
	(m^2)	*ft².*	*(BTU h)*	*(KWh)*		
Villa	710.7	7643	305720	89.59	17.9	143.2
Flat	201.6	2170	86800	25.43	5	40
Detached house	413	4445.5	177820	52.11	10.4	83.2

3. Section 3, Adaptive behaviour and thermal comfort measurements

To measure and compare the thermal comfort degree levels in the different regions of Libya.

This section consists of six questions (Q.21-Q.26).

Q.21. and Q.22 to identify the temperature set points for both periods, heating and cooling. This will help to understand and estimate the thermal comfort degree during summer and winter in the different regions of Libya. Q.22. and Q.24. the participants were asked to state the actions they do prior to switching on the mechanical equipment to feel thermally comfortable in both seasons, summer and winter. Q.25 and Q.26 both those questions were asked to measure the average time of which the mechanical equipment is in use, in both seasons summer and winter.

Q.21.During the summer, if you start feeling hot inside your house (thermally uncomfortable) at what temperature setting do you turn your AC on to cool down the room air (to feel thermally comfortable).

The results from each region are showed in the following figures.

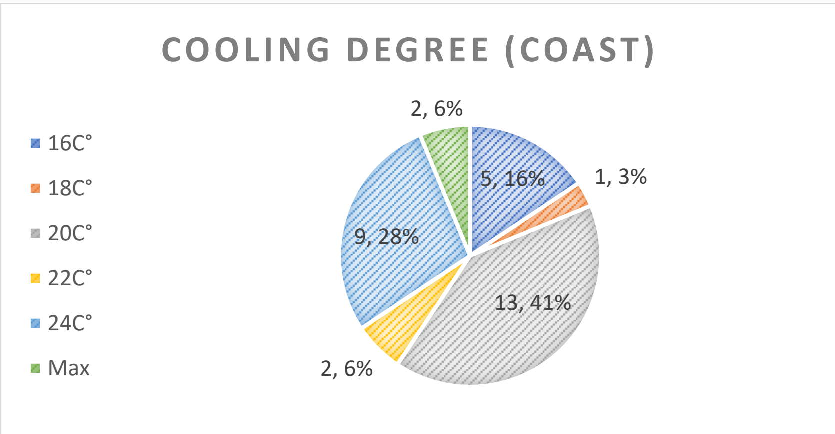


Fig.27. Cooling set point in the Coast region

In the summer, the cooling set point in the Coast region was 6% as Max, 28% is 24C°, 6% is 22C°, 41% is 20C°, and 16% 16C°.

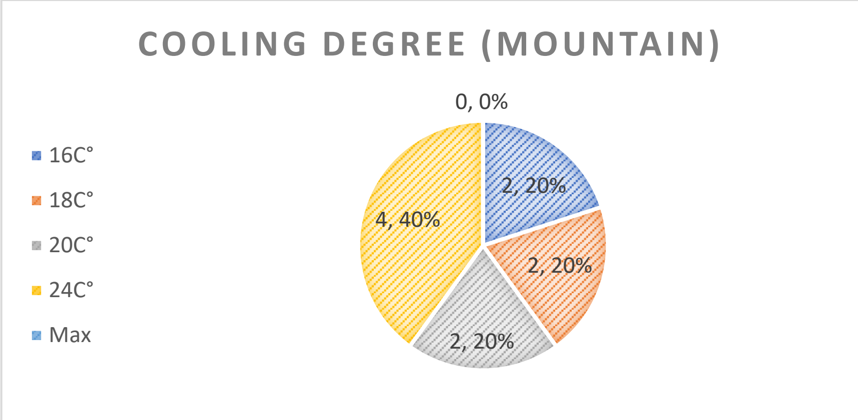


Fig.28. Cooling set point in the Mountain region

In the Mountain region, 22% answered that the set point temperature of their Air conditioners is 24C°, and on 20Cº, 18Cº, and 16Cº by 20% for each.

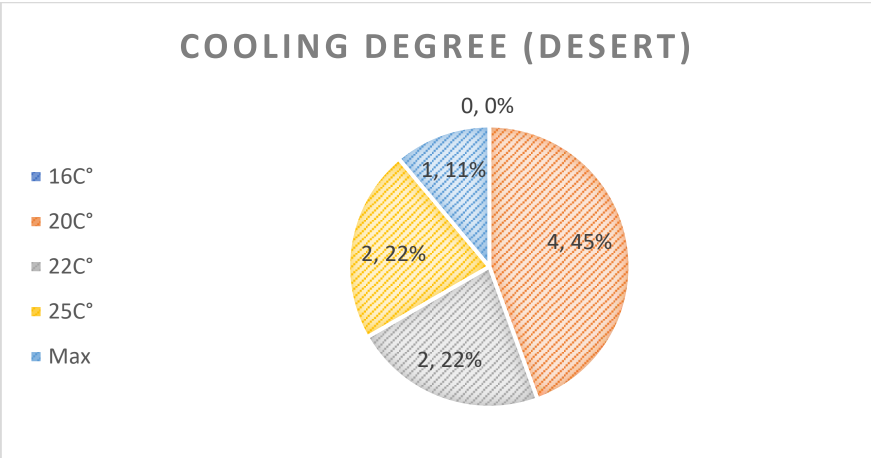


Fig.29. Cooling set point in the Desert region

For the Desert region, the temperature set point of the mechanical cooling system is 11% on the Max, both 25C° and 22C° with 22%, and 45% answered that they setup their air conditioner on 20C°.

Q.22. Before you turn the AC on, do you try any of the following?

To study the adaptive behaviour of the occupants, the participants were asked to identify the actions that they will take to enhance the thermal sensation inside their houses, before using any mechanical equipment. The answers were as follow:

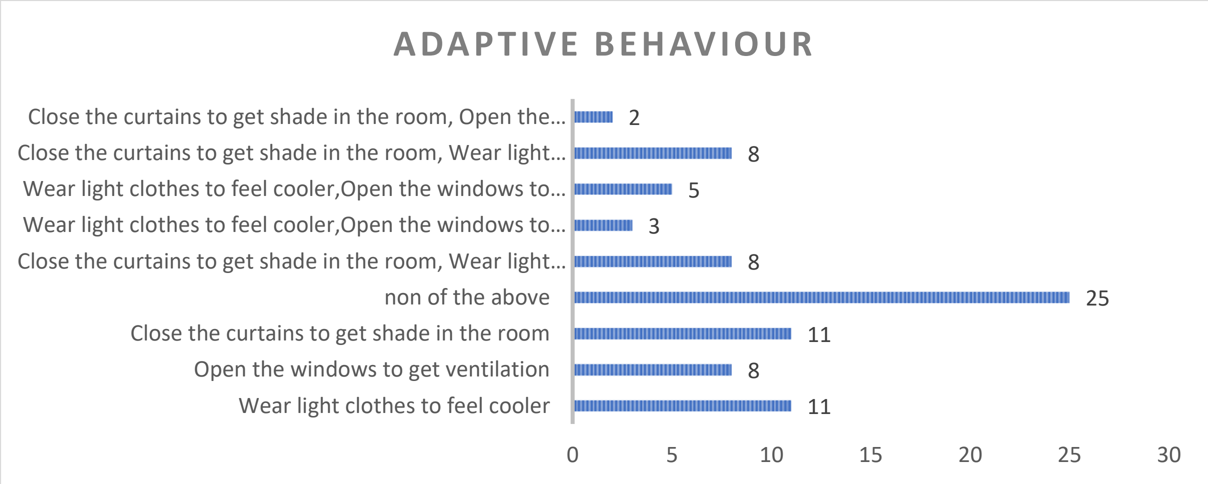


Fig.30. The adaptive behaviour of the occupants

two answered that they will close the curtains to get shade in the room and Open the windows to get ventilation, eight answered that they would close the curtains to get shade in the room and Wear light clothes to feel cooler, five wear light clothes to feel cooler and Open the windows to get ventilation, three Wear light clothes to feel cooler and Open the windows to get ventilation, eight will close the curtains to get shade in the room and wear light clothes to feel cooler, eleven close the curtains to get shade in the room, eight open the windows to get ventilation, eleven Wear light clothes to feel cooler and twenty-five answered “none of the above”.

Q.23. During the winter, if you start feeling cold inside your house (thermally uncomfortable) at what temperature setting do you turn your AC/Heater on to heat up the room (to feel thermally comfortable).

The results are analysed in the following figures.

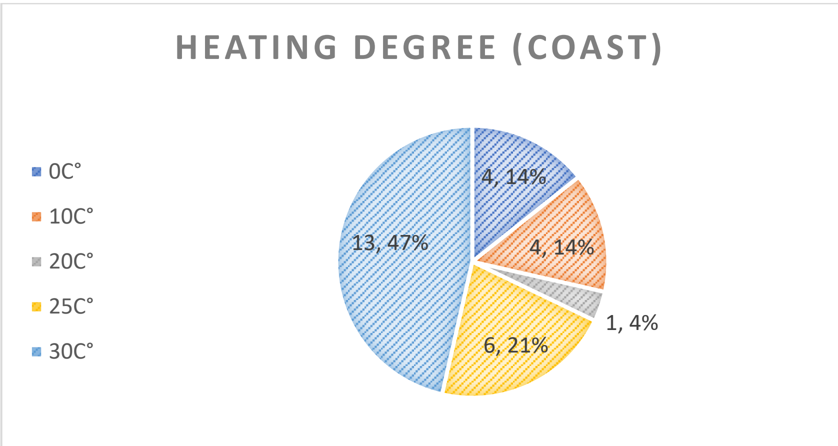


Fig.31. Heating set point in the Coast region

The figure shows that in the Coast region, heating is required during winter time. 45% stated that they adjust the temperature to be 30C°, 21% on 25C°, and 14% they have their mechanical heating equipment set point on 10C°, while 14% answered that they do not require mechanical heating during the winter.

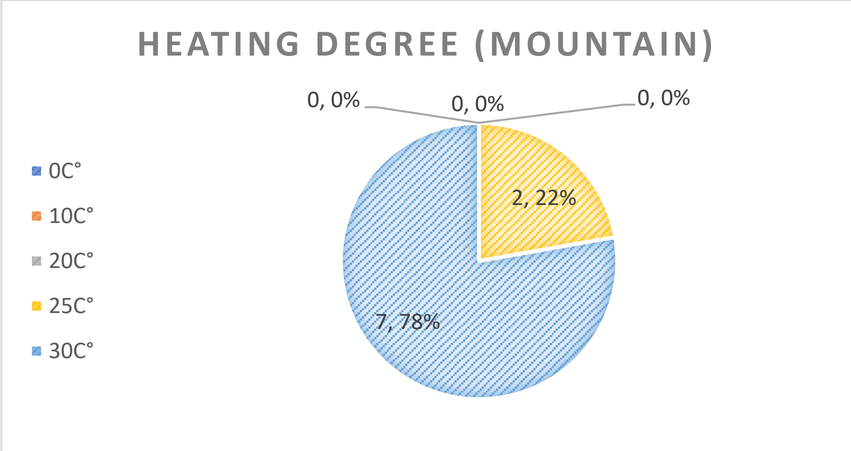


Fig.32. Heating set point in the Mountain region

In the mountain region, heatin also required during winte. The figure shows that 78% use mechanical heating on 30C°, and 22% on 25C°.

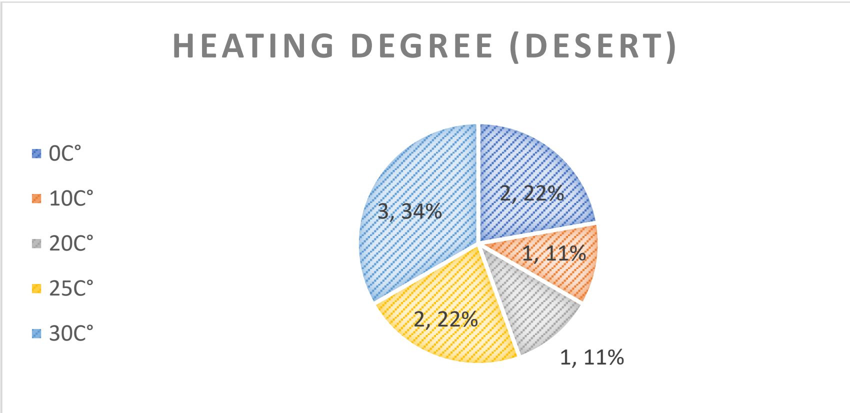


Fig.33. Heating set point in the Desert region

In the desert region, different temperature set points were recorded. 34% answered that they adjust their mechanical heating system on 30C°, 22% on 25C°, while 34% answered that they do not use mechanical equipment during winter.

Q.24. Before you turn the AC on, do you try any of the following?

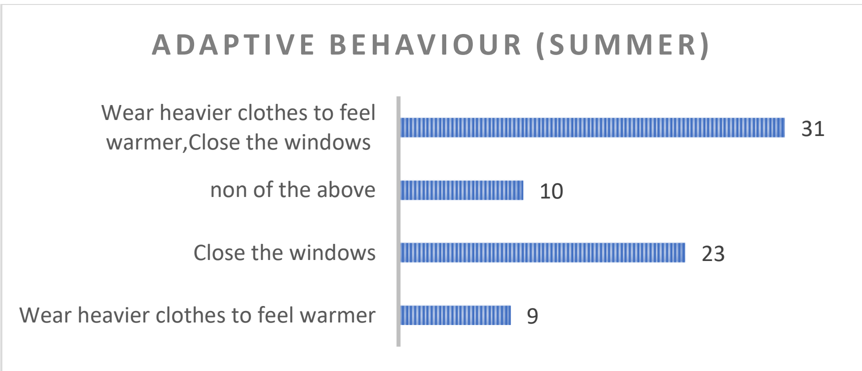


Fig.34. Adaptive behaviour during summer time

The answers show that thirty-one stated that they wear heavier clothes to feel warmer and close the windows, twenty-three Close the windows, nine Wear heavier clothes to feel warmer, and ten do not do any of the mentioned methods.

Q.25. On average, how many hours you run the heating system every day in winter?

The answers are showed in the following figure.

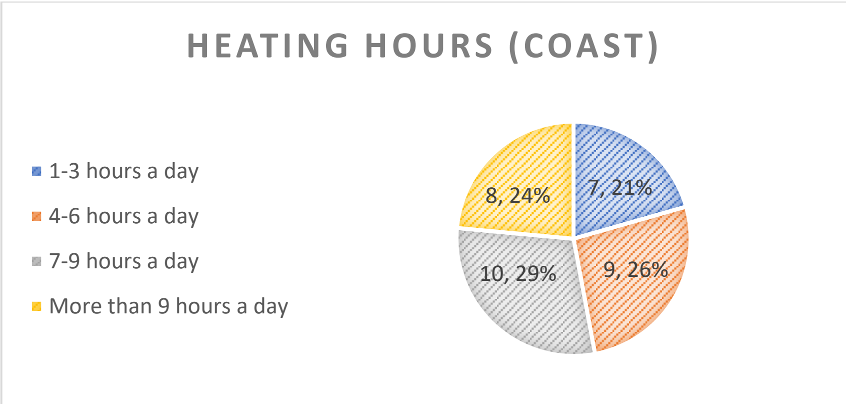


Fig.35. Daily heating hours during winter (Coast region)

The figure above shows that in the Coastal region, heating is required during winter, and for different durations. 24% answered that they need heating for more than nine hours, 29% stated that they use heating for seven to nine hours, 26% use heating for four to six hours, and 21% are using heating for one to three hours.

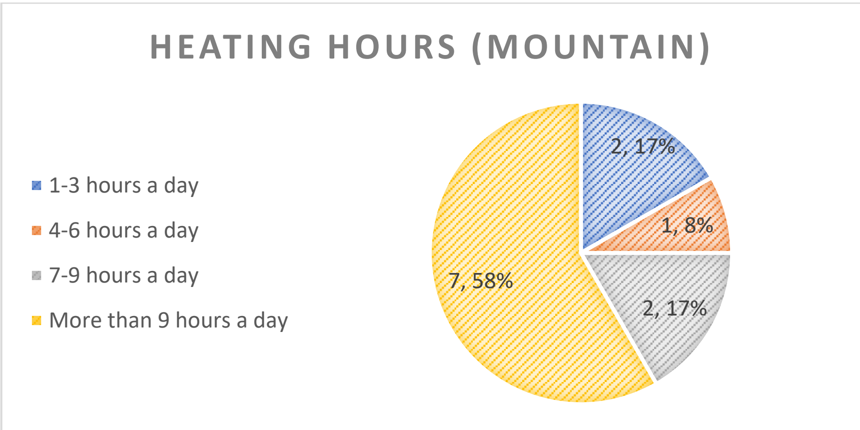


Fig.36. Daily heating hours during winter (Mountain region)

In the Mountain region, the heating hours are as follow; 58% answered that they use mechanical equipment for more than nine hours, while 17 % are using mechanical heating for four to six hours and 17% they need heating for one to three hours.

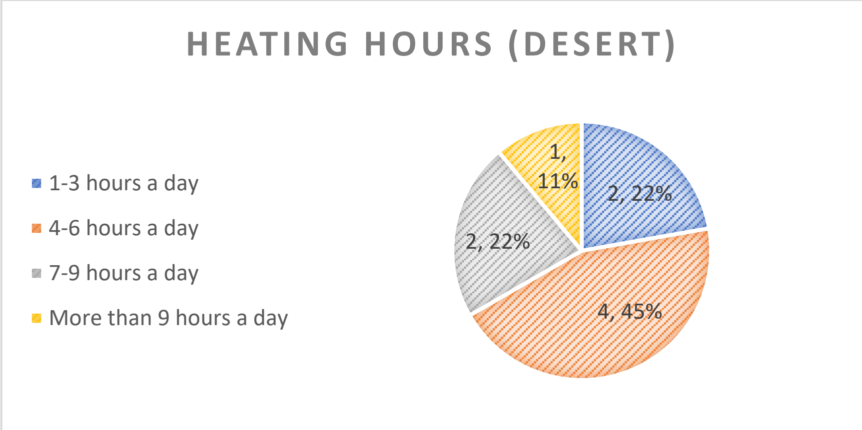


Fig.37. Daily heating hours during winter (Desert region)

The answers show that 17% use heating for one to three hours a day, 26% are using heating for four to six hours a day, 29% answered they need heating for seven to nine hours a day, and 17% are using the mechanical heating for more than nine hours a day.

Q.26. On average, how many hours you run the cooling system every day in summer?

The answer from each region are showed in the figure below.

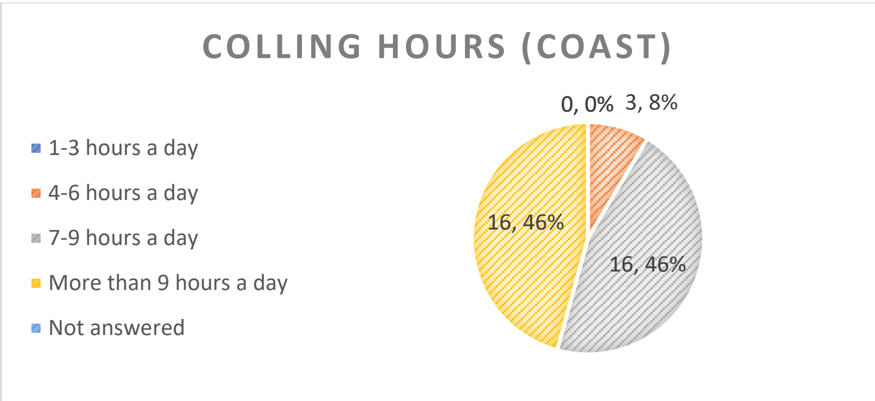


Fig.38. Daily hours of using cooling during summer (Coast region)

For the Coast region, 46% answered that they use the mechanical cooling for more than 9 hours a day during summer, and 46% are using the mechanical cooling system for seven to nine hours and 8% answered that they need cooling for four to six hours daily.

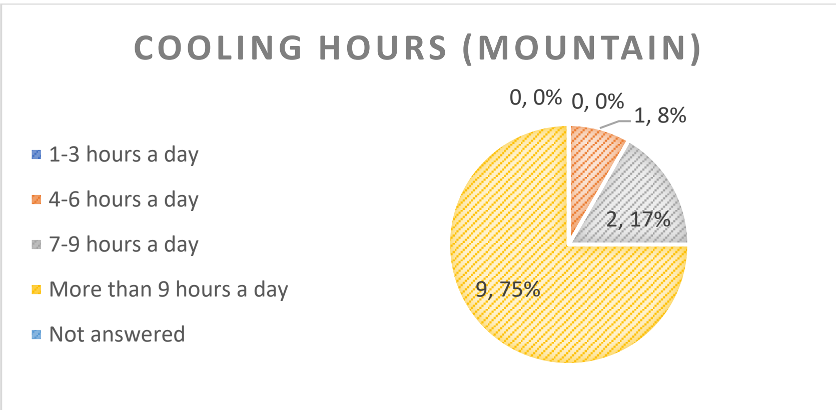


Fig.39. Daily hours of using cooling during summer (Mountain region)

In the Mountain region, 75% of the sample answered that they use cooling for more than nine hours, 17% answered that they need mechanical cooling for seven to nine hours, and 8% they use the mechanical cooling for four to six hours.

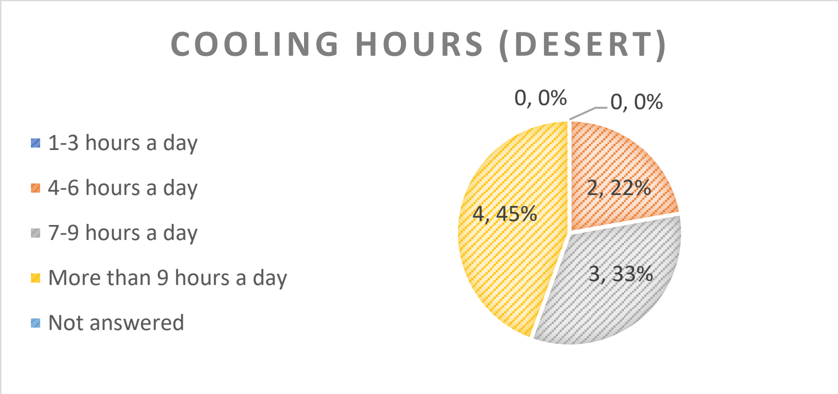


Fig.40. Daily hours of using cooling during summer (Mountain region)

In the desert region, the answers were that 45% are using mechanical cooling for more than nine hours, 33% for seven to nine hours, and 22% for four to six hours.

a. Conclusion

i. Average thermal comfort degree and the average duration of using mechanical cooling duration during summer.

The average temperature in which people feel thermally comfortable when using their mechanical equipment, and the average daily hours of using those equipment are showed in the table below.

Table.16. Average thermal comfort temperature and daily hours of mechanical cooling during summer

Region	**Thermal comfort temperature (Summer)**			**Average daily use (h)**
	Range	Average	STDEV	
Coast	9 C²	20.4 C°	2.986	10.11
Mountain	9 C²	20.2 C°	3.3	11
Desert	9 C²	21.8 C°	2.77	9.6

ii. Average thermal comfort degree and average use of mechanical heating during winter.

Table.21. shows the thermal comfort temperature during winter when using mechanical equipment, and the average daily use of heating devices during winter.

Table.21. Average thermal comfort temperature and average daily hours of using mechanical heating during winter

Region	**Thermal comfort temperature (Winter)**			**Average daily use (h)**
	Range	Average	STDEV	
Coast	22 C²	20.6C°	4.79	7.7
Mountain	7 C²	29C°	2.59	9.5
Desert	12 C²	26.6C°	4.27	6.7

4. Section 4, for specialists only (Architects, engineers, etc.)

The section was especially designed for professionals and specialists in the construction and housing industry (architects, engineers…etc.). This section contains three questions (Q.27-Q.29). In this section, the target sample were asked to state their opinion about several aspects of the Libyan architecture.

Q.27. has four sub-questions. Sub-question A. is a comparison of energy use between the modern and the traditional houses of Libya. Sub-question B is a comparison of the construction cost between the traditional and modern houses, sub-question C the use of construction material in terms of sustainability and suitability for the environment, and sub-question D is the thermal condition comparison between the traditional and the modern houses of Libya.

In Q.28. the participants were asked about the status of the traditional houses of Libya, and Q.29 is about the status of the Libyan houses in general.

The questions are analysed and presented in this section.

27. In your opinion, when comparing traditional houses to modern houses in terms of:

A. Energy use, traditional houses?

Professionals were asked to state their opinion about the energy use in the traditional and modern house. The answers are showed in Fig.41.

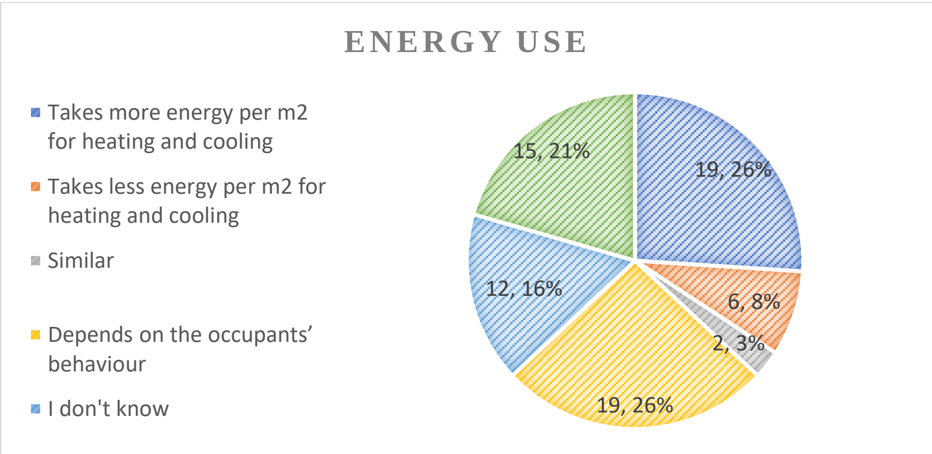


Fig.41. Energy use in the traditional houses

The answers show that nineteen professionals think that traditional houses use more energy per m² for heating and cooling, six think traditional houses takes less energy per m² for heating and cooling, two think it is similar, while nineteen thinks it depends on the occupant's behaviour.

B. Cost of construction, the traditional houses are:

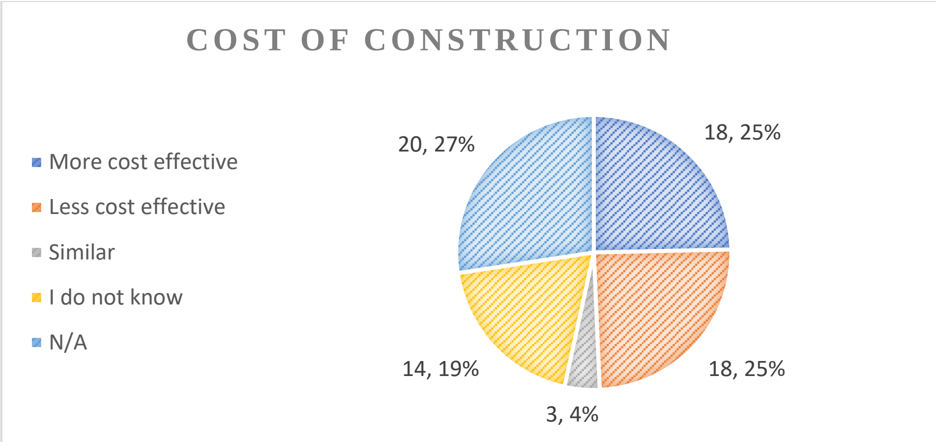


Fig.42. cost of construction of the traditional houses

In terms of construction and construction materials, eighteen professionals think traditional houses are more cost effective, three think it is similar, and eighteen think traditional houses are less cost effective.

C. The use of construction materials, the traditional houses use

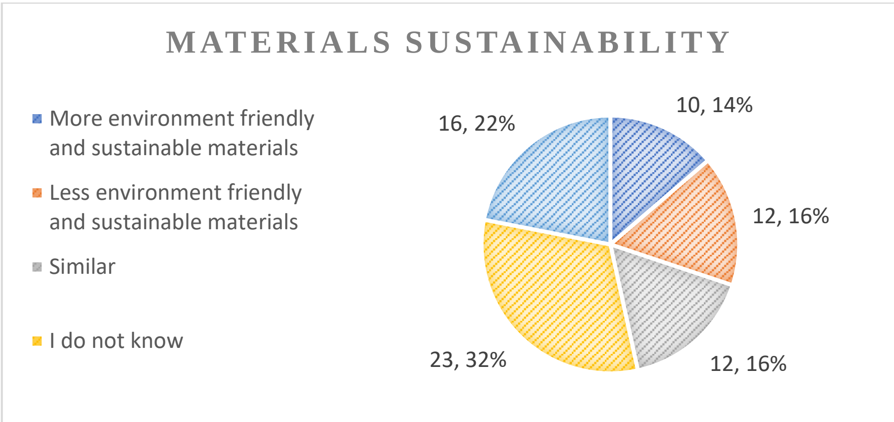


Fig.43. construction materials of the traditional houses

In term of using sustainable and more environmentally preferable materials, ten of the participants think that traditional houses use more sustainable and environmentally preferable materials, twelve thinks that the traditional materials used in the Libyan houses are less environmentally preferable materials and less sustainable, and twelve think they are similar.

D. Thermal comfort; the traditional houses provide

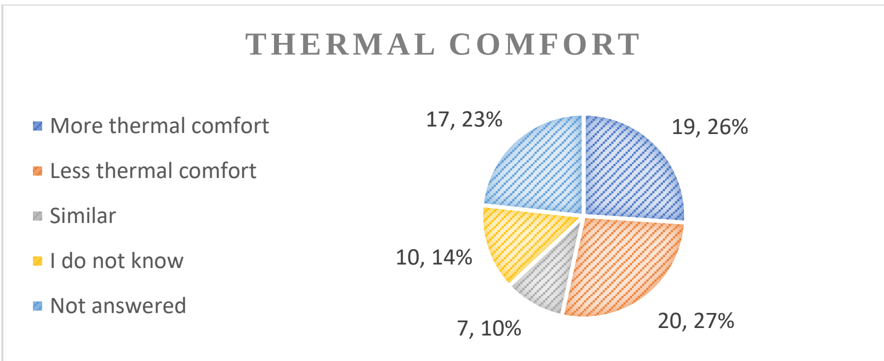


Fig.44. thermal conditions of the traditional houses

In terms of thermal comfort, nineteen thinks that traditional houses provide better thermal comfort condition than modern ones, twenty thinks that modern houses provide better thermal comfort conditions, while seven think they are similar.

Q.28. In your opinion, do you think that the traditional houses are neglected?

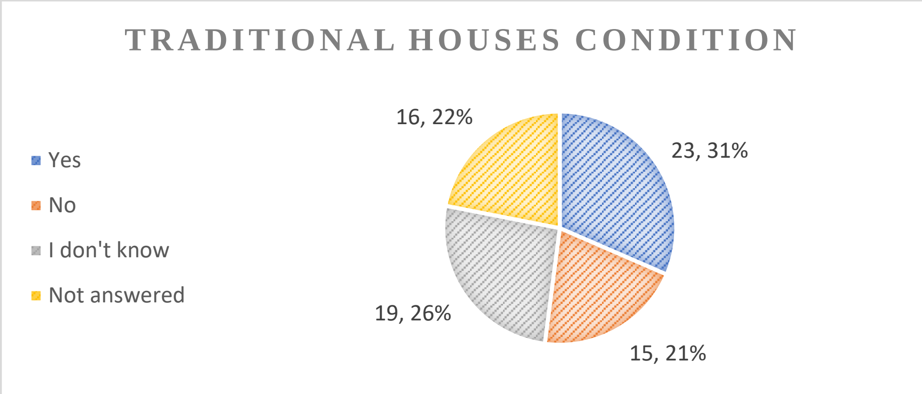


Fig.45. the status of the traditional houses

Twenty-three professionals think that the traditional houses are neglected while, fifteen answered that they are not, while nineteen answered that they do not know.

Q.29. How would you classify the current status of the houses in your country in terms of sustainability?

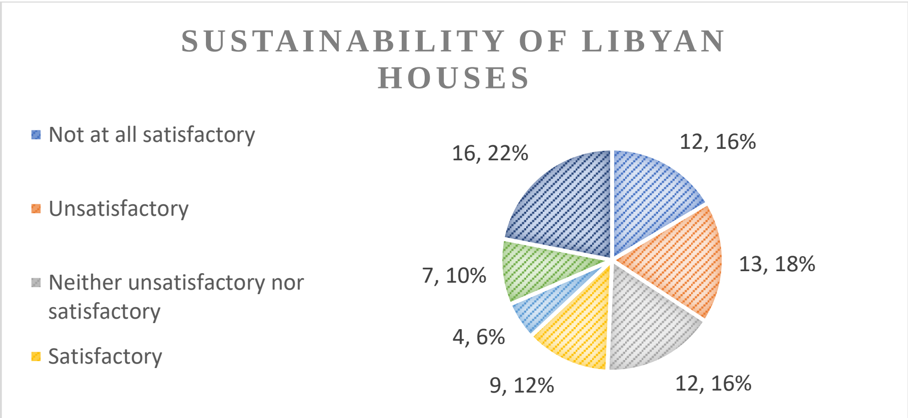


Fig.46. the current status of the Libyan houses

The figure shows that twelve professionals think that the current status of the Libyan houses, in terms of sustainability, is not at all satisfactory, thirteen think it is unsatisfactory, twelve answered neither unsatisfactory or satisfactory, nine think it is satisfactory, while four think it is very much satisfactory.

Conclusion

The study survived over seventy houses from the different regions of Libya (Coast, Mountain, and Desert). Thirty questions were distributed via emails and social media to the users of different house types in Libya.

The questionnaire was divided into four sections, each of those sections contained several questions that are designed based on the overall research objectives.

Section1, *The House Design Details*. Questions 1-16.

This section was the largest section in terms of the number of questions. Sixteen questions to inquire about the details of the houses, such as type, floor area, construction materials, thickness of the walls and roof, number of floors, number of residents, orientation of the main facades, locations and the number of openings, and the size of the courtyard.

The findings of this section are:

- In terms of house type, there are five common houses types, and the most common types are: Detached house, Villa, and Flat.
- Apart from flat, which is mostly consisting of four floors, the study showed that most of the houses are one or two floors, and in some cases three storey houses are also found.
- Different areas, ranging from, and 80m ^{2} to 2,000m^2 were found, and the average area for each house type, with the average area per person (m^2) were also calculated.
- In terms of envelope details, different thickness and different materials for walls and roofs are found. The result showed that in the Coast and Desert region, the dominant construction material for walls is Hollow concrete blocks, and for the Desert region, the most used construction material was Limestones blocks. For roofs, in all regions, the main construction material is Concrete.
- In terms of windows, different sizes are found, but mostly, medium sized windows (1m*1.2m) are used. The average window area for each house type and the WFR% calculations were made.
- In terms of building orientation, the findings showed that there was no real consideration to building orientation, despite of it is important for both, thermal condition, and energy performance of the house. The houses in each region seemed to be randomly oriented with different orientations in each region.

Section 2, *Energy Use in the Libyan houses.* Questions 17-20.

This section was aiming to getting some background information regarding the energy performance of the Libyan houses, and to try to identify the energy use and energy consumption of the Libyan houses.

In this section, energy use calculations were made. The estimated costs for lighting, and for some domestic appliances were also calculated in this section. Additionally, some general calculations for space heating and cooling loads for each house type were also made.

Section 3, ***Adaptive behaviour and thermal comfort measurements***, questions 21-26.

This section aims at understanding the adoptive behaviour of the Libyan household in response to the thermal conditions inside their houses.

In this section, the thermal comfort degrees for both seasons (summer and winter) in all the regions of Libya were calculated. The findings of this section also showed that most of the occupant are responding to the thermal conditions by switching their mechanical equipment without doing any passive actions, such as wearing heavier clothing or shading the room. This indicate the need for some controlled passive solutions to be used in the Libyan houses.

Some calculations, such as the thermal comfort degree and the average operation times of using the mechanical equipment, were also made at the end of this section.

Section 4*, for specialists only (Architects, engineers, etc.), questions 27-30.*

This is the final section of this survey, which is targeting the professional in the Libyan construction industry. Participant were asked some questions to try and identify and compare some key aspects of the modern and traditional houses of Libya. Those aspects included: energy use, cost of construction, construction materials, thermal comfort, current condition of the traditional house's conditions, and the overall houses condition in terms of sustainability and suitability for the Libyan environment.

The overall findings of this study will be tested and used, along with other data, to construct and outline some guidelines and principle for designing and optimizing more sustainable and more environmentally suitable houses in Libya.