Low Energy Building Material Suitable for Bhutanese Architecture – Wood Wool Slab

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Thesis for the degree of Master of Engineering in Renewable Energy

Division of Heat Transfer
Department of Energy Sciences

Faculty of Engineering | Lund University

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This degree project for the degree of Master of Engineering in Renewable Energy has been conducted at the Division of Heat Transfer, Department of Energy Sciences, Faculty of Engineering, Lund University.

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Abstract

Rammed earth is commonly used to construct traditional Bhutanese buildings. In colder areas, the thermal performance of these buildings is poor leading to the easy ingress of cold air demanding more heating energy to make a comfortable indoor climate. Modern insulation materials are not common in Bhutan due to the lack of knowledge on the advantage of thermal insulating materials, the unavailability of local insulating materials, and the cost associated with them. The construction in urban areas is dominated by modern building materials such as concrete and bricks nevertheless rural areas prefer the use of local materials. To improve the indoor environment, new bio-based building insulating material called wood wool slab was introduced. As a pilot project, the Bhutanese blue pine was used as the main raw material to manufacture wood wool, and cement was used as a binder to prepare wood wool slabs in two different methods. Three different specimen was made and tested in civil engineering laboratory for the bending strength test, among which specimen 3 stands the highest bending force 584 N at a displacement of approximately 11 mm whereas specimen 1 and specimen 2 resist a force of nearly 300 N. Thermal conductivity test was also performed in physics laboratory by Hot Disk (TPS 2500S), however, the test was unsuccessful due to uneven surface of the specimen that provides defective results. In the performed simulations, the value from the Swedish wood wool slab results was used to compare the thermal performance and energy performance in unheated cases, 2 kW cases, and 10 kW cases.

The comparison was made with rammed earth and burnt bricks. The highest energy consumption in a year was 24123 kWh in rammed earth buildings, followed by burnt bricks with 17922 kWh and the lowest was 6576 kWh for wood wool slab buildings. Accordingly, the thermal performance of these three building materials was compared in an unheated case. The wood wool slab has shown better performance which means that it can retain heat for a longer duration. This result indicates that the wood wool slab can be a good alternative for the Bhutanese construction industry to make buildings thermally comfortable and energy-efficient.

Acknowledgment

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I will always remain in debt to Dr. Henrik Davidsson for being supportive and generous in every field during my study period from day one until the end. Finally, I would like to take this opportunity to thank my family members for their moral support and passion.

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List of Abbreviations and Acronyms

ASHRAE	American Society of Heating, Refrigerating and Air Conditioning Engineers
BBR	Bhutan Building Rules
CAGR	Compounded Annual Growth Rate
DEROB-LTH	Dynamic Energy Response of Building - Lund Institute of Technology
DIN	German Institute for Standardisation
DRE	Department of Renewable Energy
GWh	Gigawatt Hour
ISO	International Organization for Standardization
kL	Kiloliters
kWh	Kilowatt-hour
MoWHS	Ministry of Works and Human Settlement
MT	Metric Ton
NEC	National Environment Comission
NSB	National Statistics Bureau
PMV	Predicted Mean Vote
PPD	Predicted Percentage Dissatisfied
RCC	Reinforced Cement Concrete
WWCB	Wood Wool Cement Boards
WWCP	Wood Wool Cement Panels
WWS	Wood Wool Slabs
λ-Value	Thermal Conductivity

Chapter 1 Introduction

1.1 Background

Bhutan is unique in terms of cultural and traditional values, and the built environment. The marvelous fortresses, tranquil temples, stupas, and vernacular farmhouses with a pristine environment result in an intricate pattern that reveals the richness of cultural heritage(MoWHS, 2014). However, urbanization and the introduction of modern system development impair the natural and built environment. Some of the massive challenges are the adaptation of new methods and materials in building construction, the overexploitation of natural resources, and disturbances in architecture's social and spiritual beliefs. Bhutan has undergone an immense change in building construction methods and materials used over traditional ones. The use of modern materials including brick, concrete, glass, steel, etc. leads to the decreasing trend of rammed earth, stones, and timber(DRE, 2015). The country is very careful about the challenges while embracing modernization. The various regulations and directives are describing how to build a building and house with concern to Bhutanese architecture guidelines.

Housing is one area where culture and tradition can be promoted. Initially, Bhutan Building Rules 2002 was amended to ensure and facilitate safe building construction that promotes a quality living environment at the same time keeping intact distinct architectural design(Department of Urban Development & Housing, 2002). As time changes with the use of sustainable and efficient technologies, few provisions in BBR -2002 have become redundant.

In the year 2018, BBR-2002(Department of Urban Development & Housing, 2002) was reviewed. The new Bhutan Building Regulation 2018 was formed to foster safe functional and accessible settlements; improve the standard and quality of people’s lives and preserve and promote pure cultural landscapes. This regulation stimulates and facilitates energy-efficient housing which is environmentally friendly and establishes the standards for the construction of buildings in line with the traditional architectural design(Department of Human Settlement, 2018). Most vernacular houses are built from locally available materials such as timber, rammed earth, stones, and bamboo depending on the weather conditions of the places, nonetheless modernization has penetrated even in the countryside where people prefer easier and more readily available materials such as cement and concrete.

Bhutan has three distinct climatic zones: subtropical in the south, temperate in the central, and harsh alpine in the northern regions(MoWHS, 2013). Consequently, these diverse climatic conditions mean that people living in different zones require specific design considerations and materials used to have climate-resilient dwellings. However, the lack of such standards and regulations results in the use of readily available building materials (modern building materials) such as brick and concrete, steel, and glass which leads to energy-inefficient buildings. According to the Bhutan Building Energy Efficiency Study, a shift in the building material from mud and rammed earth to brick, concrete, and any other modern structures have increased the heat loss from walls to almost 1.7 times during the period 2007 – 2012(DRE, 2015). A huge amount of thermal or electrical energy is required in the building sector (42 % of total energy consumption in 2014) to make the home comfortable during harsh weather conditions(DRE, 2019). The burning of firewood to heat the home challenges Bhutan’s commitment to remain a carbon-neutral country(NEC, 2020). Cold houses also bring health issues. When looking for alternative methods to make home energy-efficient and pleasant, it's critical to keep the environmental effect minimal while maintaining the houses' architectural identities.

1.2 Aim and objectives

This research intends to integrate traditional Bhutanese construction techniques with low-energy alternatives to create more energy-efficient and comfortable homes with eco-friendly materials while preserving a unique architectural heritage. This technique is compatible with traditional Bhutanese architecture and has the potential to preserve Bhutanese architecture. It will facilitate the reduction in energy consumption and increase thermal comfort in buildings. Therefore, the project's main goal is to advance knowledge on global sustainability material practices and encourage research and development aimed at producing a climate-resilient building material that reduces energy consumption and environmental degradation while also producing high-quality building materials that improve indoor environmental quality. Moreover, to notify the advantages of thermal insulation materials and their availability within a locality.

1.3 Research scope

Bhutan's contemporary buildings and vernacular houses are neither energy-efficient nor comfortable for living, especially in the winter season. This study is intended to explore eco-friendly and sustainable alternatives to the current building materials and methods to make homes safe and comfortable. This study is in line with the National Energy Efficiency and Conservation Policy(DRE, 2019) to satisfy some of its key elements and fulfill some aims of the Bhutan Green Building Design Guidelines(MoWHS, 2013). Besides improving the indoor environmental quality, using wood wool cement products that have better thermophysical properties will help to reduce the enormous amount of heating energy, importantly burning firewood and the usage of electric heaters for space heating. Consequently, the conservation of forests and the environment.

1.4 Research Approach

The field research of this study was conducted in Bhutan though the main laboratory research was carried out at Lund University, Sweden. The main goals of the research were to evaluate the physio-thermal properties of wood wool slabs (WWS) samples along with their mechanical properties test. Then the simulation work was carried out to assess the potential of the material to improve thermal comfort.

The wood wool slab samples were prepared in the laboratory, at Lund University from Bhutanese pine wood that is locally available in Bhutan. The thermal conductivity test for both isotropic and anisotropic was carried out using Thermal Constants Analyser (TPS 2500 Hot Disk®) in the Physics Laboratory of the Building Material Division. The bending strength test was also performed in the Civil Engineering Laboratory.

However, the thermal conductivity test results are used in simulation which was performed using DEROB-LTH to evaluate the energy performance and thermal performance of the Bhutanese building apartment and compare the with the other building materials.

Chapter 2 Literature Review

2.1 Building Construction Materials in Bhutan

Bhutan is well known for its traditional architecture and extensive use of wood for construction. The building construction and materials used differ from the climatic zones. In Bhutan Building Energy Efficiency Study, it was found that there is a difference in the construction of rural and urban buildings. The use of modern construction materials on large scale like steel, glass, and reinforced concrete (RCC) was seen widely in urban areas while rural construction adhered to the preservation of culture and tradition using locally available materials. The traditional *Sa Khem* (Earth House) is prevalent in rural areas(DRE, 2015).

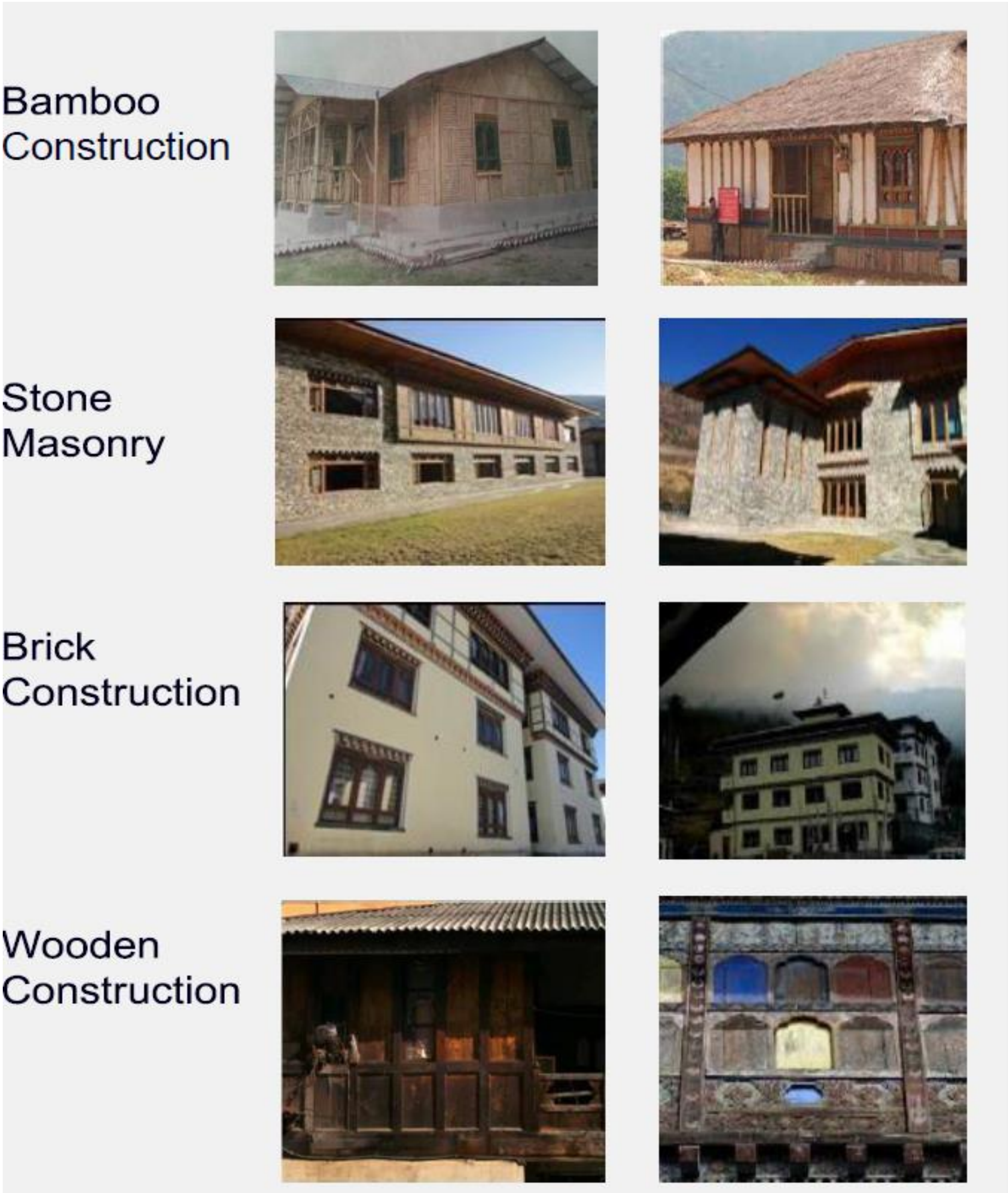


Figure 2.1: Wall materials used in Bhutan(DRE, 2015).

Figure 2.2: Traditional rammed earth and stone-wall buildings (MoWHS, 2014).

The minimum thickness of the rammed earth wall is 500 mm and the thickness of the wall increase with the increase of the building storey(DRE, 2015).

Bhutan Travellers also stated that the major building blocks of Bhutanese architecture are natural and locally available, including earth, timber, stones, and bamboo(Travellers Bhutan, 2021). Traditional methods are still used in the construction of houses in Bhutan. The walls of the houses are built of mud and rammed earth and timber is primarily used despite inexpensive materials such as cement and concrete being readily available. The walls and roofs of those houses have gaps to facilitate airflow and are specially designed based on the local weather conditions.

According to Bhutan Living Standards Survey Report 2017, the mud-bounded bricks, or stone-walled dwellings (35.9 %), are prominent, followed by the cement-bounded bricks or stonewalls holding 24.6 %. The dwellings are also made of concrete (13.9 %) and wood or branches (12.9 %). This report reveals that the use of concrete and cement-bounded or stone as a main exterior wall material increases while other materials such as wood or branches, mud-bounded bricks, or stone decrease with an increase in per capita household consumption quintile(NSB, 2017).

2.2 Thermal Energy Consumption in the Building Sector of Bhutan

The building sector in Bhutan accounts for 15 % or 319 GWh of the total electricity consumption of a country which is around 2094 GWh leading to an increase in domestic electricity demand and a decrease in the export by 8.7 %. Thermal energy consumption contributes to 4 % of total consumption(DRE, 2015).

According to Bhutan Energy Data Directory 2015, the building sector contributes 42 % of total energy consumption in 2014(DRE, 2016). Heating, cooking, and lighting draw a huge amount of energy, especially in residential buildings. There has been a transition in energy source usage from biomass (fuelwood) to electricity in recent years.

Table 2.1: Residential Energy Use by Segment (Building Sector) – 2014(DRE, 2016)

Fuel	**Units**	**2005**	**2014**	**CAGR (%)**
Electricity	GWh	89.31	211.85	10.07
Kerosene	kL	6442	3402	-6.85
Biomass	MT	543503	494831.2	1.04
Liquefied Petroleum Gas	MT	3522	6348.6	6.77

From Table 2.1, it is observed that the fuelwood (biomass) for space heating is reduced by 1.04 %, which is being substituted by the electric heater with a significant increase in electricity usage. However, in institutional and commercial segments the building sector has more demand for fuelwood and electricity for heating and cooking as shown in Table 2.2.

Table 2.2: The breakdown of energy use in the institutional and commercial sectors -2014(DRE, 2016)

Fuel	**Units**	**2005**	**2014**	**CAGR (%)**
Electricity	GWh	51.86	107.3	8.41
Kerosene	kL	5828	2271	-9.94
Biomass	MT	74065	119838.2	5.49
Liquefied Petroleum Gas	MT	950	681.3	-3.63

In colder districts, the heat loss from the wall ranges from 40 % to 70 % depending on the materials used. In contrast, rammed earth has minimum and brick wall has maximum heat loss. Since almost all the windows are single glazed it also leads to significant heat loss of around 20 % to 25 %(DRE, 2015). Consequently, there is a higher percentage of electric heater users in urban areas (50.7 %) and a few proportions in rural areas (10 %) as well. The firewood consumption is nearly 90 % for both cooking and heating. The usage of *bukhari* (wood stoves) is prevalent in rural areas (31.3 %) compared to urban areas (13.9 %) as a source of energy for heating(NSB, 2017). The detailed heating energy sources are shown in Table 2.3.

Table 2.3: Household Distribution by Energy Use and Source, as well as by Area (Urban or Rural)(NSB, 2017)

Use and Source of Energy	**Urban**		**Rural**		**Bhutan**	
	Number	**%**	**Number**	**%**	**Number**	**%**
Heating	58333	100	105678	100	164011	100
No Heating	17543	30.1	31574	29.9	49116	30
Bukhari (wood stove)	8134	13.9	33119	31.3	41253	25.2
Electric Heater	29544	50.7	10197	9.7	39741	24.2
Kerosene Heater	2643	4.5	494	0.5	3137	1.9
Gas Heater	77	0.1	0	0	77	0.1

Straw/brush/manure stove	57	0.1	207	0.2	264	0.2
Thab (Traditional stove)	336	0.6	30088	28.5	30424	18.6

2.3 Availability of Raw Materials Locally

It is difficult to conclude that the wood species in Bhutan is suitable for wood wool slabs. It should undergo full-scale testing, which requires access to the wood shredder machine. Fortunately, numerous wood species are already tested, among which some of these species exist in Bhutan. These woods are considered suitable only if they meet the bending test requirement of DIN1101 or an equivalent standard(Johansson, 1994). Some of the wood species found in Bhutan are mentioned in Table 2.4.

Table 2.4:Trees suitable for wood wool slabs(Johansson, 1994)

SL. No.	Botanical Name	Suitability
1	Albizia falcataria	Suitable
2	Albizia lebbek	Suitable
3	Anisoptera costata Korth	Suitable
4	Bombax cieba	Suitable
5	Bridelia retusa	Suitable
6	Calophyllum inophyllum	Suitable
7	Cedrela toona	Suitable
8	Cedrus deodara	Suitable
9	Cordia myxa	Suitable
10	Dipterocarpus sp. (“gurjan”)	Suitable
11	Eucalyptus globulus	Suitable
12	Mangifera indica	Suitable
13	Picea smithiana	Suitable
14	Pinus wallichiana	Suitable
15	Pinus roxburghii	Suitable
16	Salmalia malabarica	Suitable
17	Syzygium cumini	Suitable
18	Shorea ovalis Bl.	Suitable

2.4 Wood Wool Slab as Building Materials

To make the wood wool cement board, Kelempayan trees are shredded in wood wool and mixed with Portland cement (WWCB). The WWCB samples' properties such as swelling, bending, and compression strength were all investigated. 75 mm WWCB has a higher fracture toughness than 50 mm WWCB, but it has a lower strength. The findings suggest that the WWCB is also suitable for load-bearing because its mechanical properties are comparable to those of other load-bearing elements like masonry and straw bale walls(Ahmad et al., 2018).

Similarly, a study is being conducted on Malaysian fast-grown timbers to produce wood wool cement boards. The density, flexural, compressive, and tensile strength of wood wool with diameters of 1.5 mm, 2.5 mm, and 3.5 mm and board thicknesses of 25 mm, 50 mm, and 75 mm were determined. It is concluded that density has a significant impact on the mechanical properties of the WWCB. The WWCB's strength is reduced as its density decreases(Johansson, 1994). The density of the wood wool decreases as the size of the wood wool increases, so the smallest size of wood wool and the smallest thickness of the board will have greater flexural strength, while the compressive strength was high in thick panels(Ahmad et al., 2011).

Even though the use of wood wool cement composite was limited to non-structural applications such as boundary walls, ceilings, soundproofing, and decorative panels, (Noh et al., 2016) demonstrated that the wood wool cement panel (WWCP) has the potential to be used in structural applications because its mechanical properties meet the ISO and DIN 101 minimum requirements(Ahmad et al., 2011). As a prefabricated wall, the structural performance of the 1 200 mm * 1 200 mm (30 mm) WWCP has significantly increased the stability and load-carrying capacity.

A preliminary study by Alex Lyatonga Mrema looked at the different wood wool-to-cement ratios as well as the width of the wood wool. The best mix ratio was three parts cement to two parts wood wool, with the smaller width of wood wool providing more strength by increasing the surface area of adhesion between the binder and the substrate(Mrema, 2006). The tensile, flexural, and compressive strength test results go above and beyond the German Standard DIN 1101:1989.

There are other associated benefits of using wood wool slabs. It has good acoustic properties, where the sound insulation increases with the addition of cement plasters. The material is classified as hard to ignite and resist fire at certain hours depending on the thickness of the WWS. The fire performance of the material is related to the coverage of wood stands by the binders (cement, gypsum, magnesite), hence resistance to the insects and termites as well as resistance to rot and mould. Moreover, it has good moisture-absorbing properties that are suitable in the places like sports complexes where the relative humidity is occasionally very high(Johansson, 1994).

Chapter 3 Research Methodology

3.1 Reference Building

Figure 3.1 is in the capital city of Bhutan at an altitude of 2358 m above sea level. It is in temperate climatic conditions where the temperature is cool in summer and cold in winter. The burnt bricks with cement plaster are the main building wall materials.

Figure 3.1: Isometric view of a building for the study

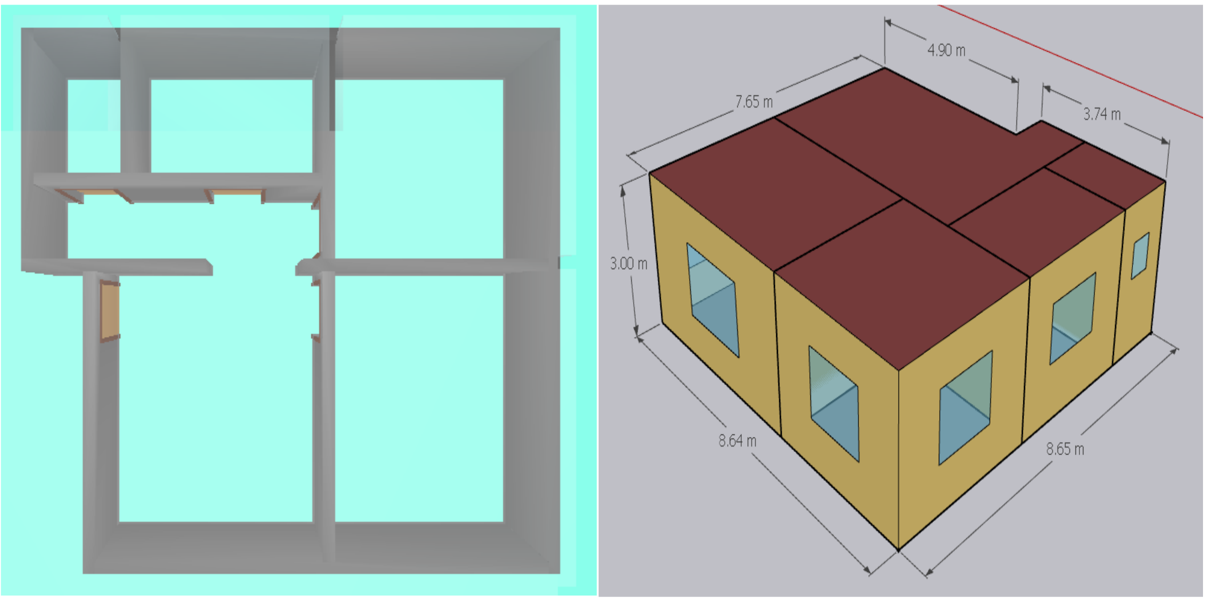


Figure 3.2: Plan view of an apartment for the study

3.2 Building Dimensions

The measurement in Figure 3.2 is all based on inside measurements. These dimensions are important to construct a model to evaluate the heating energy demand and thermal performance of a building. The actual dimensions of an apartment are given in Table 3.1, but the details of the dimensions used in the simulation are given in the APPENDIX.

Table 3.1: Actual dimensions of an apartment.

Surface Type	Materials	Thickness (mm)
Wall	Cement plaster and burnt brick	275
Floor	Timber Flooring, concrete cast slab reinforced	210
Ceiling	Timber Flooring, concrete cast slab reinforced	210
Window	Glass	6
Door	Hardwood	30

3.3 Blower Door Test

A depressurization blower door test was performed with the help of Fantestic Retrotec equipment sets. The equipment sets consist of a variable speed fan, fan speed controller, adjustable door frame, and a manometer. The experiment is carried out to investigate air leakage in a room. The volume of air removed out of the openings of the fan was determined and measured at 50 Pa for 10 minutes. The test results are shown in Table 3.2.

Table 3.2: Blower door test summary

retrotec FanTestic	version:**5.11.79**	licensed to: **College of Science and Technology**
Test date: **2021-03-08**	By: **Dekar Wangchuk**	
Customer:	**Tshering Phuntsho**	
Building Lot Number:		
Building address:	**Above CDCL building Thimphu, Bhutan**	

Building and Test Information	
Test file name:	**EN13829-EU 2021-03-08 1618**
Building volume [m³]:	**169.3**
Envelope Area [m²]:	**123**
Floor Area [m²]:	**24**
Building Height (from ground to top) [m]:	**3**
Building Exposure to wind:	**Partially protected building**
Accuracy of measurements:	**10%**

Results	
Air flow at 50 Pa, [m³/h]	**1021.5**
Air changes at 50 Pa, n_{50} [/h]	**6.04**
Flow per Envelope Area at 50 Pa, [m³/h/m²]	**8.303**
Flow per Floor Area at 50 Pa, [m³/h/m²]	**42.564**
Effective leakage area at 50 Pa, [cm²]	**311.5**
Equivalent leakage area at 50 Pa, [cm²]	**510.5**
Leakage per Envelope Area at 50 Pa, [cm²/m²]	**2.5309**
Leakage per Floor Area at 50 Pa, [cm²/m²]	**13.0**

The above result showed that the air changes at 50 Pa were 6.04 per hour, and the leakage was 8.303 $m^3/h/m^2$.

Figure 3.3: Blower door experiment arrangement

3.4 Materials and Methods

This study was made possible primarily due to the corporation between Lund University, Division of Heat Transfer, and College of Science and Technology, Bhutan. This research includes the laboratory-based sample making of the wood wool slab with the Bhutanese Blue Pine, and the thermal properties testing. As a part of field research, the visit was made to one of the automated wood wool slab factories in Sweden.

In the first phase, the local raw materials suitable for wood wool production were identified and blue pinewood species were selected. The debarked Bhutan blue pine was cut into blocks of 50 cm (Figure 3.4) and shipped to Sweden. The wood was shredded into 2.5 mm (Figure 3.6) size and approximately 200 mm long in the factory during the field visit.

A visual live inspection of how a factory is operating and a short in-person interview with the factory owner on the processes of manufacturing were also carried out. Following are the pictures that reveal the functioning of the factory and its end products.

Figure 3.4: Local raw material (blue pine)

Figure 3.5: Blue pine billet pushing into a shredding machine

Figure 3.6: The shredded wood wool

Figure 3.7: Compressed wood wool cement boards

Figure 3.8: Wood wool cement wall and bricks

Figure 3.9: Finished products for different functions

In the second phase, the wood wool slab samples are made of local raw materials (Bhutanese blue pine). The experts are involved in preparing the samples and carrying out the λ-value test in a laboratory.

The two types of wood wool slabs are prepared as specified in Table 3.3 and Table 3.4 below. Specimen 1 was prepared by mixing dry cement with wet wood wool (soaked in clean water). Specimen 2 was made of a mixture of dry wood wool and cement slurry. Both mixtures were arranged in the mould manually and then compressed with the heavyweight and let dry for not less than two nights. Then the slab was carefully removed from the mould and let cure for a month. Pictorial processes are shown in Figure 3.10 and Figure 3.11.

Table 3.3: Composition of specimen 1

Number	Materials	Quantity (kg)
1	Wood wool	1.8
2	Cement	2.4

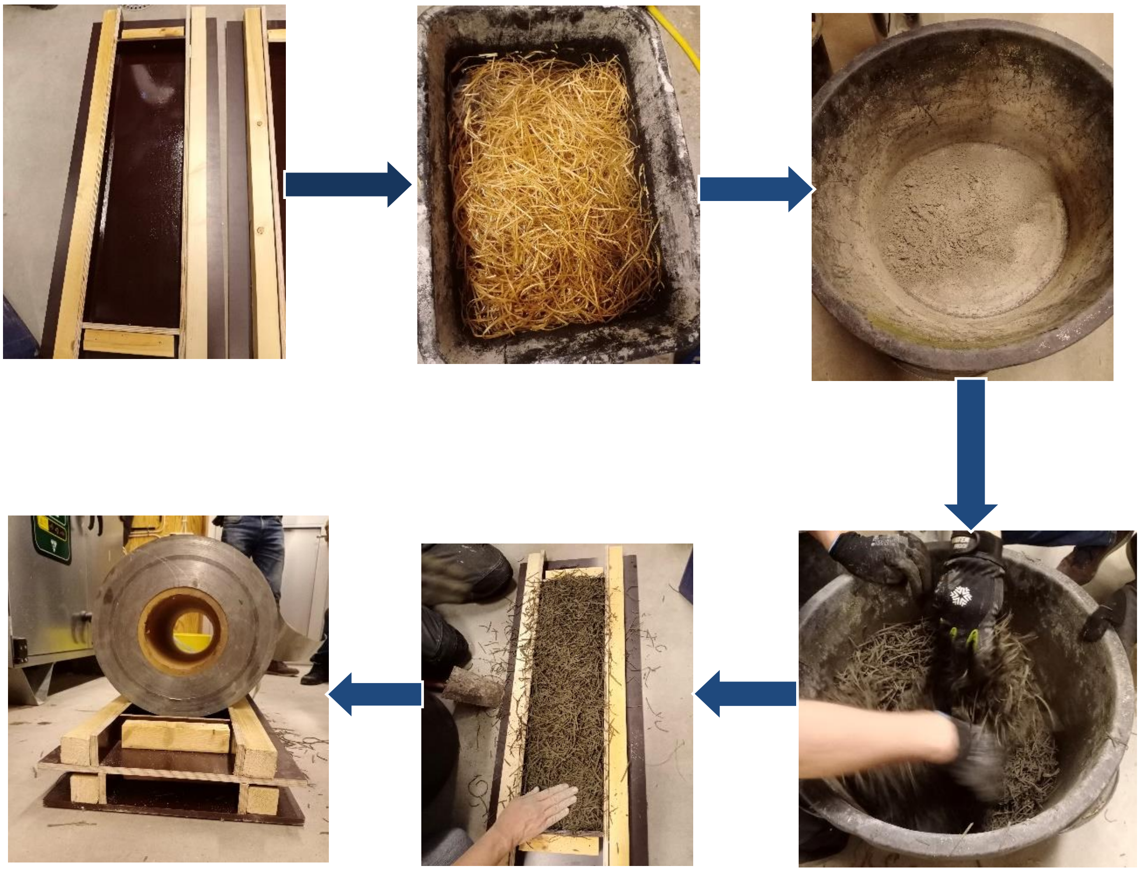


Figure 3.10: Procedure of specimen 1

Table 3.4: Composition of specimen 2

Number	Materials	Quantity (kg)
1	Wood wool	1.2
2	Cement	2.4
3	Water	2.5

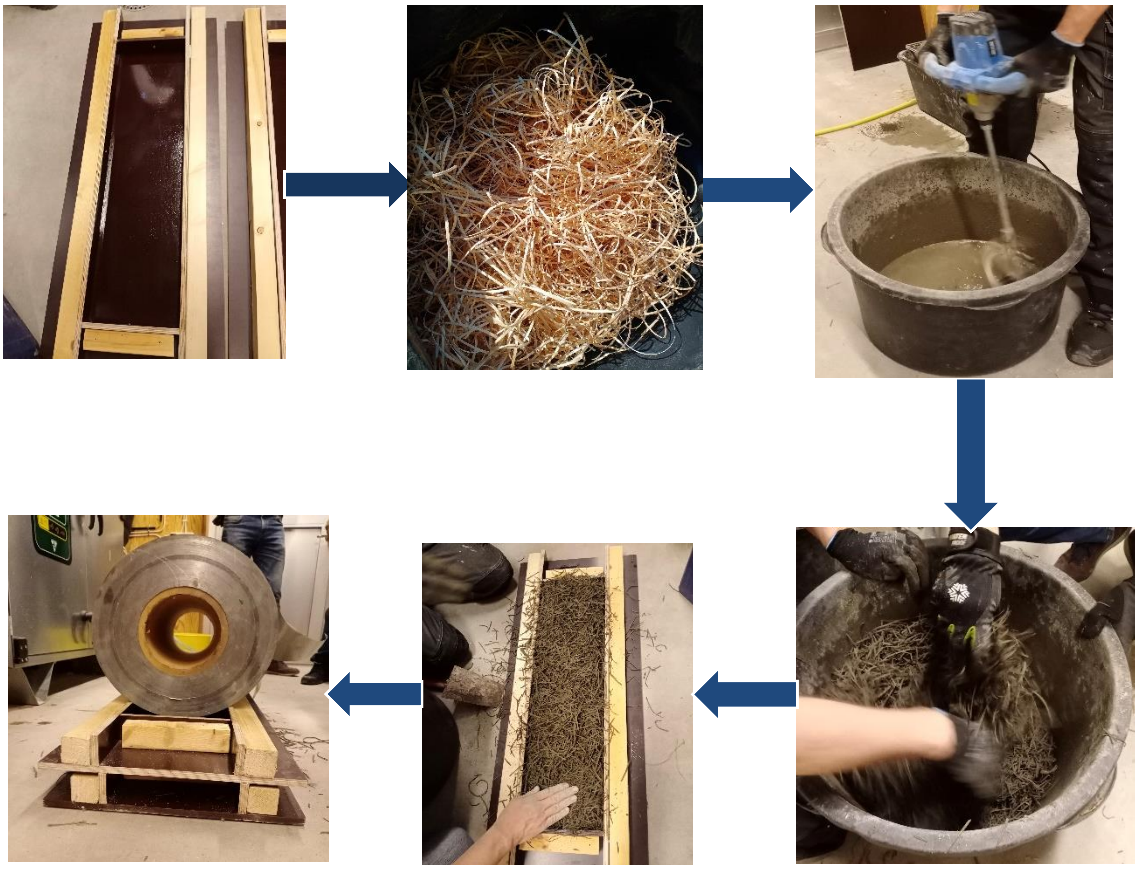


Figure 3.11: Procedure of specimen 2

The wood is shredded in 2.5 mm normal size in the factory whereas the sample preparation was carried out in the laboratory of Lund University with the help of experts and researchers on wood wool slabs. To have proper binding, wood wool and binder (grey cement) were thoroughly mixed and laid over the mould in such a way that wood wool strands were horizontal and straight which will help to give better mechanical and thermal properties.

Similarly, another specimen was prepared by myself without involving the experts with the following composition.

Table 3.5: Composition of specimen 3

Number	Materials	Quantity (kg)
1	Wood wool	1.3
2	Cement	2
3	Water	2

The Swedish thermal conductivity test value of 0.085 W/mK(Johansson, 1994) will be taken as a reference to validate the accuracy level of the Bhutanese thermal conductivity value for the wood wool slab. If the results are not reliable, the Swedish λ-value will be taken into consideration for simulation.

In the last phase, a simulation study was carried out to understand the heating energy demand in the Bhutanese apartment.

The modeling of a Bhutanese apartment with simplified dimensions is shown in Figure 3.12. The sketching of the building model was carried out in DEROB-LTH. All the building elements are assigned according to the in-situ measurement dimensions shown in Figure 3.2 however some of the dimensions are simplified for ease of modeling and simulation according to the conditions and goals of the simulation. The details of building element and their composition and dimensions are given in APPENDIX Table 1.

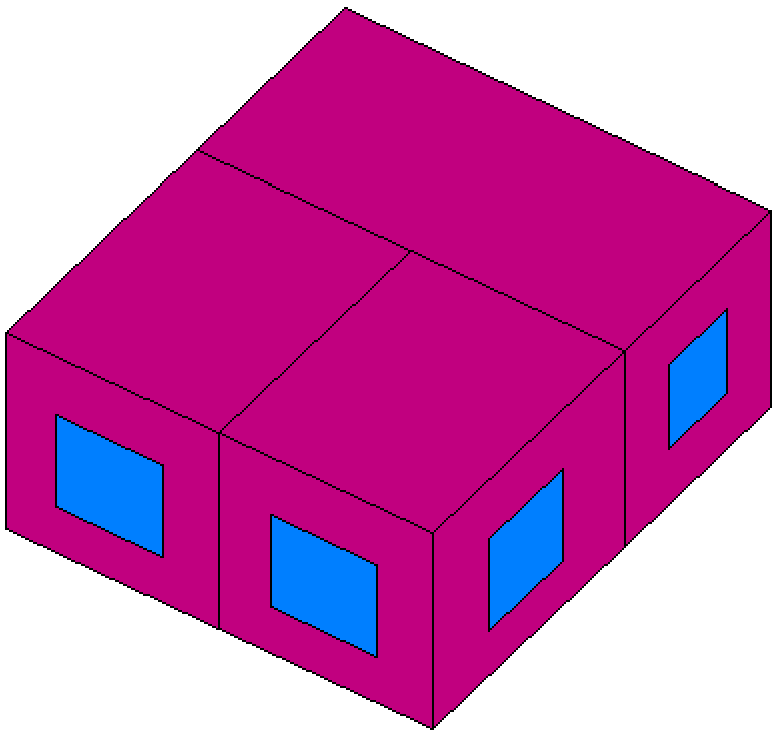


Figure 3.12: Perspective view of building apartment model

The schedule sets, the activity of occupants, internal gains, and hours of operation of the electrical equipment are all assigned according to the real-time operation of an apartment.

To understand the energy performance and thermal performance of wood wool slabs, the three different cases of energy simulation at 20 °C indoor temperature for all three volumes were performed and the results were compared with the energy performance of rammed earth and burnt brick buildings.

The thermal comfort of building materials was evaluated according to ASHRAE standard 55-2004. Six primary factors influence thermal comfort, i) metabolic rate ii) clothing insulation iii) air temperature iv) radiant temperature v) airspeed, and vi) humidity. The environment required for comfort is different and difficult to satisfy everyone in space. However, the acceptable thermal environment for general comfort was given by ASHRAE based on the thermal sensation scale.

Table 3.6: Acceptable thermal environment for general comfort(ASHRAE, 2004)

PPD	PMV Range
< 10	$-0.5 < PMV < +0.5$

3.5 Model Control Method

Model control or validation is one of the most important approaches before carrying out the main simulation. Simulation models are becoming more popular as a tool for problem-solving and decision-making. The developers and users of these models, as well as decision-makers who use information derived from the models' results and those who are influenced by judgments based on these models, are all concerned about whether the model and its results are acceptable(Robert G. Sargent, 2010). It verifies the accuracy of the model we built and assures that the results obtained are satisfactory. In this study, the model reliability was examined in three different methods. The very basic model control was to check if all the surfaces are facing toward the correct side with all the wall surfaces facing outside should be in purple and the surface facing inside brown. Likewise, the glass is sky blue, and the floor is dark blue.

The second model control method was a simulation of transmission losses in a steady state without sun, ventilation, internal loads, outside temperature (0 °C), and setting the indoor temperature at 20 °C. The total heating energy demand was compared with the simple UA-value degree hour model calculation of transmission losses. The hand calculation of transmission losses for a model was 36781 kWh and the simulation result was 31240 kWh. There was a 5541 kWh heat demand difference because the cooling from the wall via radiation is not into account.

To confirm further accuracy, the third control method was adopted with constant ventilation and figuring out the heating demand which should correspond to the hand calculation of ventilation losses. The heating energy demand in 0.3 $l/s \cdot m^2$ and 1.1 l/sm^2 was evaluated in simulation and the difference was 1885 kWh. On the other hand, ventilation losses were 1879 kWh. The result was so close to each other.

Another control was done by adding internal load and actual leakage of the house preferably without insolation to check how much heat demand is reduced. This result was compared to the simulation result without internal load. The difference should approximately correspond to the annual estimated internal loads. The heating energy demand difference was 5758 kWh while the total annual internal load was 5945 kWh. In this case, the mismatch was around 3.14 % which is an acceptable range. The details of these calculations was shown in the APPENDIX.

Chapter 4 Results and Discussion

4.1 Bending Test

The bending test was conducted in the Civil Engineering Laboratory, with the help of a hydraulic machine. All three specimens mentioned in Table 3.3, Table 3.4, and Table 3.5 were tested to confirm the deformation when it is loaded for a certain time. Each WWS is placed on two supports as shown in Figure 4.1 at a span of 68 cm from the center of the two supports.

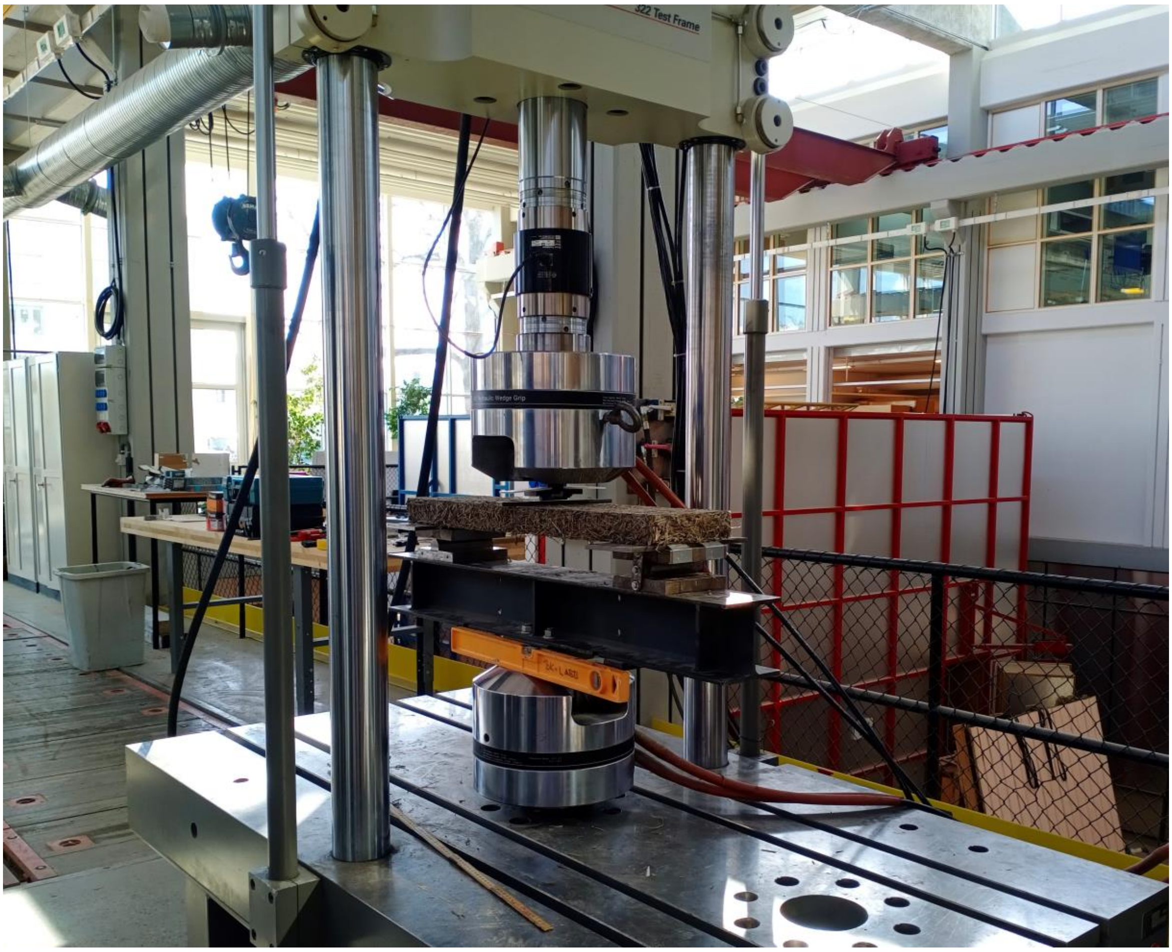


Figure 4.1: WWS placed on the two support for bending strength testing

The WWS was loaded linearly parallel across the two support as shown in Figure 4.2. The load is steadily increased until it breaks down and starts bending.

Figure 4.2: Loaded WWS and deformation of the specimen

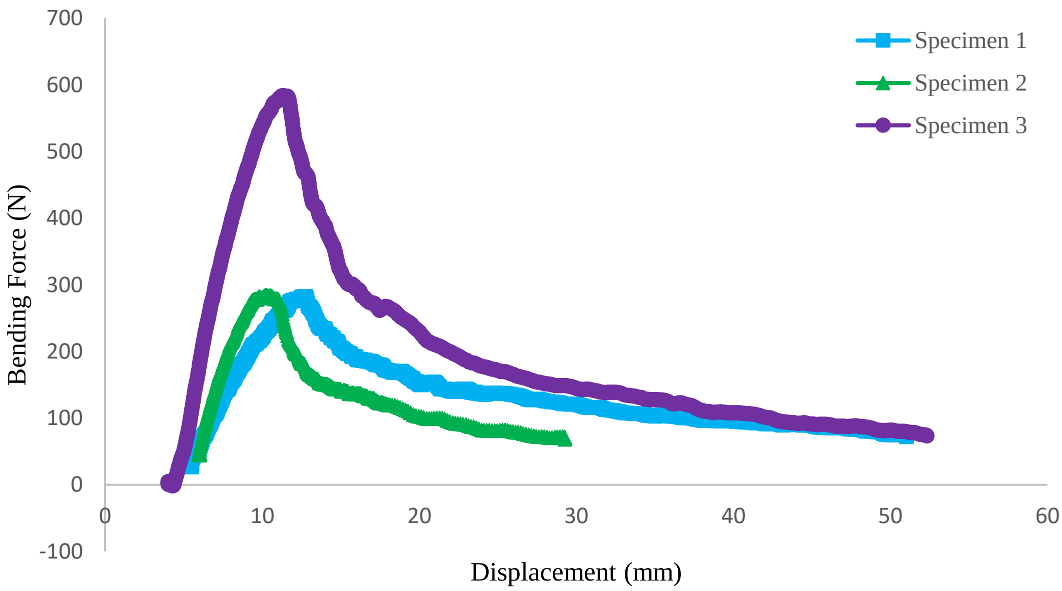


Figure 4.3: Bending Strength plot of three different specimens

From Figure 4.3, it is observed that Specimen 3 tolerates the highest bending force 584 N at a displacement of 11 mm whereas Specimen 1 and Specimen 2 resist a force of nearly 300 N. The results differ especially due to the mixing ratio of wood wool and binder as shown in each composition table. The wood wool slab can be one of the suitable building materials in earthquake-prone areas because it does not break down instantly as seen in the above graph unlike concrete, bricks, etc.

The bending resistance of each specimen can be calculated using the following formulae.

Moment in three-point bending.

$$M = \frac{P * L}{4}$$

Where P is force (N) and L is span (m)

Moment resistance (for a rectangular beam)

$$W = \frac{b * h^2}{6}$$

Where b is breath and h is the height of the specimen

Stress (σ)

$$\sigma = \frac{M}{W}$$

Table 4.1: Maximum stress each specimen can resist

WWS Specimens	Bending Resistance (kN/m²)	Density (kg/m³)
1	625	275
2	620	413
3	1,284	408

Mathematically shown in APPENDIX, and from Table 4.1, it can be concluded that specimen 3 has better bending strength (1,284 kN/m²) compared to the other two specimens. The density of each specimen was also calculated after weighing them individually.

4.2 Thermal Conductivity Test

The thermal conductivity (λ- value) of wood wool slabs is primarily determined by their density and moisture content; as density and/or moisture content rises, so does thermal conductivity(Johansson, 1994). The test was carried out in the physic laboratory under the Division of Building Materials.

Figure 4.4: Sensor C5599 in between WWS for λ-value test

As shown in Figure 4.4, the WWS was sawed into small pieces for λ-value testing with the help of Hot Disk (TPS 2500S) by placing a sensor C5599 in between two pieces of WWS. The test was unsuccessful due to the uneven surface of the WWS which provides unreliable results. An anisotropic measurement was done, and the axial λ-value was 0.023 W/m·K and the radial λ-value was 0.88 W/m·K. Anisotropic measurement was varying from 0.08 W/m·K to 0.154 W/m·K. The results obtained from the test were not consistent and accurate. Therefore, the simulation was performed using the Swedish thermal properties of WWS (APPENDIX) that were measured in the factory precisely.

4.3 Energy Performance of Building Materials

Table 4.1 shows the results for three cases. Case 0 kW is when there was no heating device in any of the volumes, hence zero energy consumption. In the case of 2 kW which means that the 2 kW heater was used in each volume to maintain the minimum indoor temperature up to 20 °C. The highest energy consumption was seen in the rammed earth buildings with 24,123 kWh in a year, followed by burnt bricks building and WWS house consumes the least with only 6,576 kWh per year in total for three volumes, revealed in Table 4.2. In the case of 2 kW, it was understood that the heating energy supply was not sufficient to meet the minimum indoor temperature set point. Therefore, a case of 10 kW was performed to confirm the final energy consumption by maintaining a minimum of 20 °C inside each volume as shown in Table 4.2. It was noticed that there is a small increment in the energy consumption in rammed earth and burnt bricks buildings when there is more energy supply however WWS building requires only a 2 kW heater or of less rating to maintain a minimum indoor set point. Replacing rammed earth by WWS can save 17,547 kWh.

Table 4.2: Energy consumption in comparison for different building materials

	Wood Wool Slab (kWh)	Rammed Earth (kWh)	Burnt Bricks (kWh)
CASE 0 kW	0	0	0
CASE 2 kW	6,576	23,767	17,902
CASE 10 kW	6,576	24,123	17,922

4.4 Thermal Performance of Building Materials

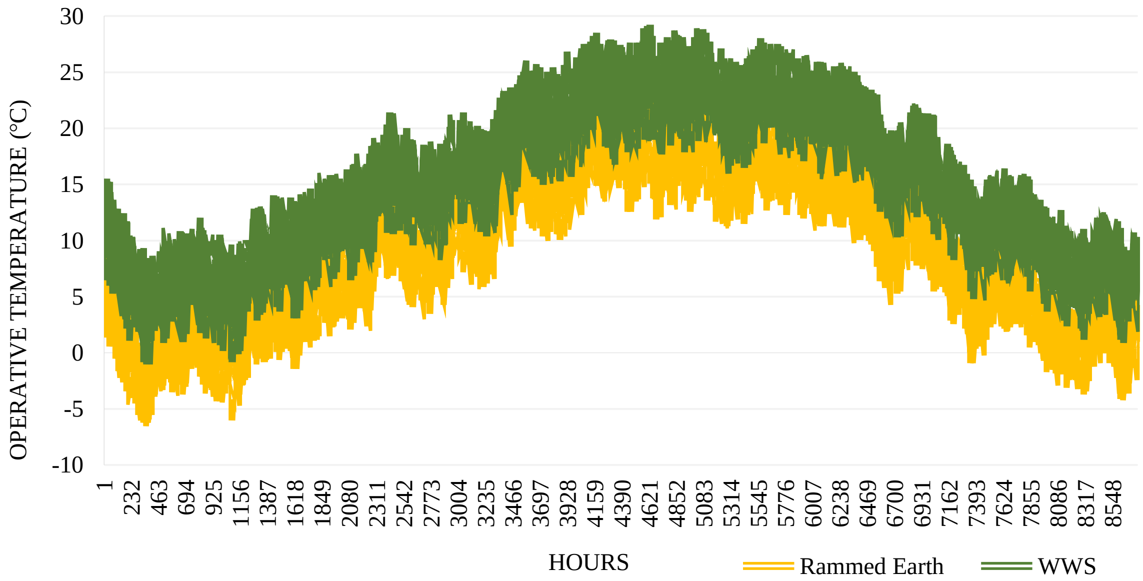


Figure 4.5: Thermal performance without heating (CASE 0)

Figure 4.5 reveals the actual thermal performance of wood wool slabs compared to rammed earth when there is no heating system in the room. Vividly, the WWS outperforms the rammed earth throughout the year. The rammed earth building experience negative operative temperature especially in winter months whereas the WWS building performs better at least maintaining an operative temperature of above 0 °C.

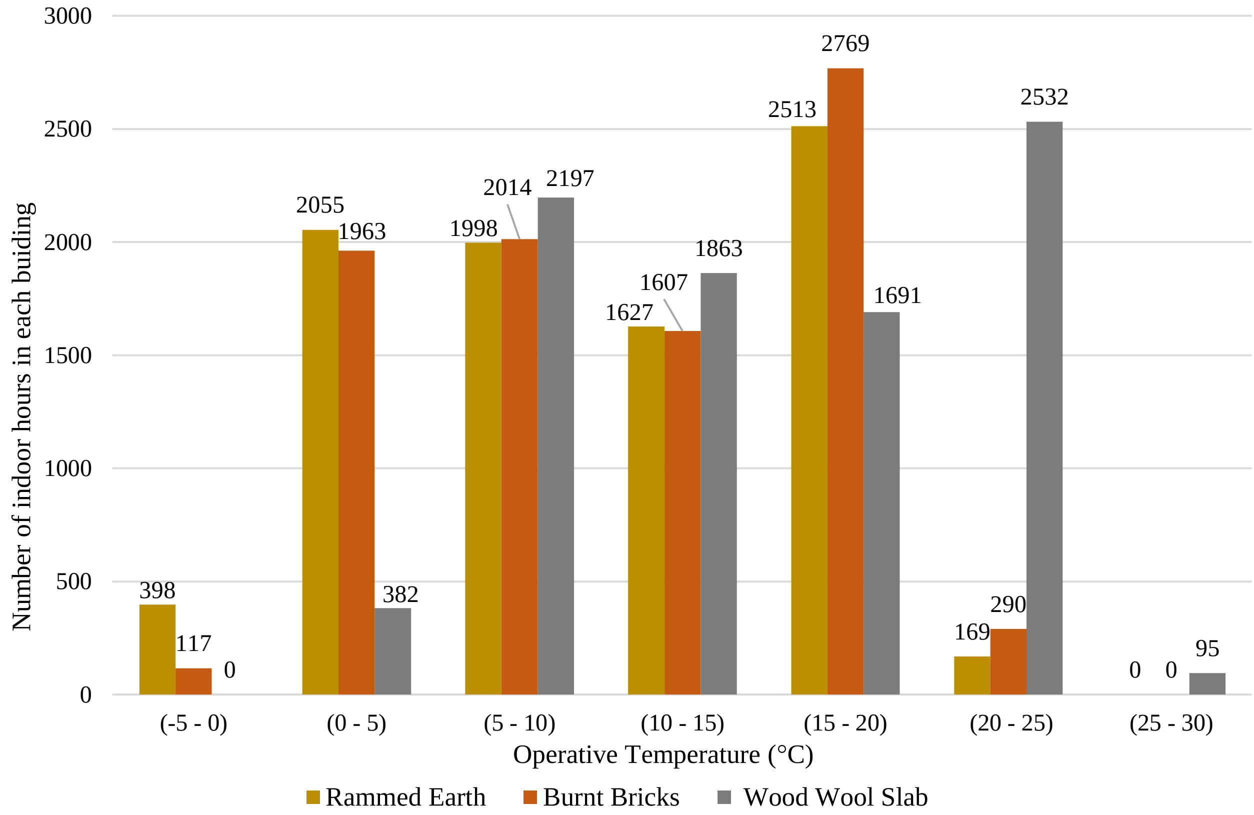
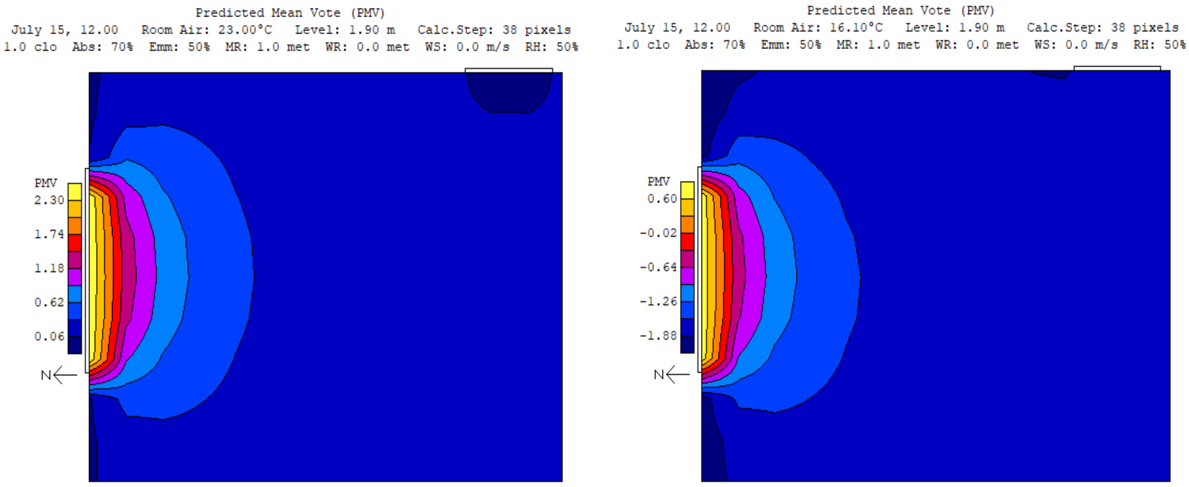


Figure 4.6: Thermal performance of building materials in the unheated condition

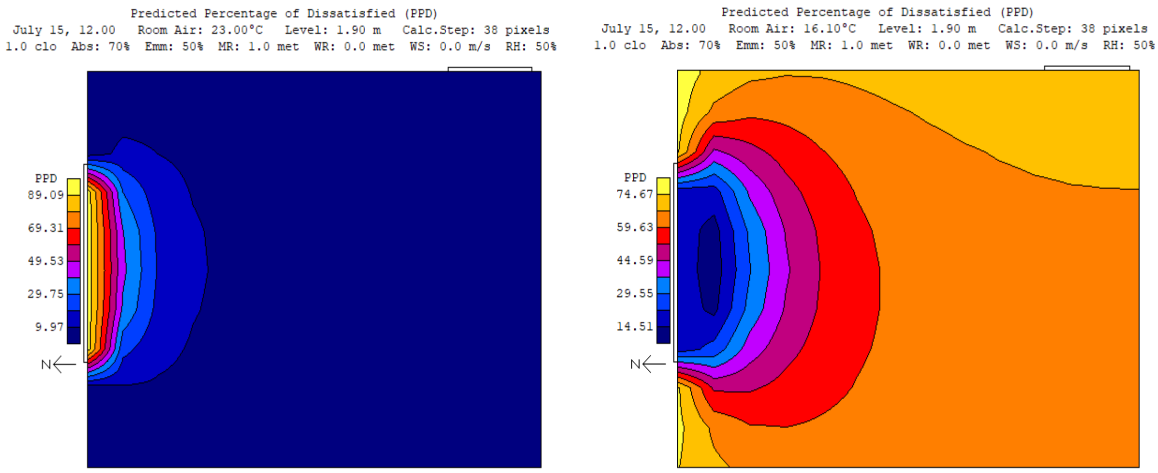
From this plot, Figure 4.6, the clear distinction of thermal performance at different temperature ranges can be understood for WWS, rammed earth, and burnt bricks. The simulation study was carried out for these three different building materials without a room heating system. It was shown that there are 398 hours in rammed earth, and 117 hours in burnt bricks which are below 0 °C to -5 °C. Similarly, there are a huge number of uncomfortable hours for rammed earth and burnt bricks buildings in the operative temperature range from 0 °C to 5 °C whereas there are only a few hours in WWS buildings. Conversely, there are more numbers of comfortable hours in WWS buildings while there is comparatively fewer in the other two buildings in the operative temperature range of 20 °C to 25 °C. This operative temperature range based on humidity ratio is normally acceptable and considered as comfortable for an indoor environment(ASHRAE, 2004). There are also a few hours in the temperature range of 25 °C to 30 °C. However, it should be noted that natural ventilation with opening windows was not included in this investigation. Opening windows has the potential to reduce the number of hours uncomfortably high indoor temperatures.

Further, the comparison was made between WWS and rammed earth building materials for four different months in a year however July month results were much better to show the difference in the performance of each material. The comparison was done under CASE 0 kW where there was no heating energy supply. The following compared results are only for volume 1, however, the results of volume 2 and volume 3 are also similar.



(a) (b)

Figure 4.7: (a) PMV of WWS & (b) PMV of Rammed Earth for July month



(a) (b)

Figure 4.8: (a) PPD of WWS & (b) PPD of Rammed Earth for July month

Predicted mean vote (PMV), and predicted percentage of dissatisfied (PPD) of people depending on the six primary factors was examined for all the months however, it is worth comparing for July which gives better results for discussion. In Figure 4.7, the pattern looks similar nevertheless it can be differentiated from their scale.

Figure 4.7 illustrates the PMV graph for WWS building (a) and rammed earth (b). It was seen that the room air temperature was 23 °C in the WWS building and the minimum PMV was 0.06 inside the room, which is in the acceptable range, but the PMV value goes beyond the range when it approaches the window making people feel uncomfortable (hot). On the other hand, PMV values of the rammed earth building inside the room are unacceptable with the room air temperature at 16.10 °C, the PMV improves only near the window.

Figure 4.8 depicts the PPD graph for WWS (a) and rammed earth (b). It was observed that the WWS building has a minimum of 9.97 PPD which is less than 10 PPD that can be considered a comfortable and satisfying indoor environment. However, rammed earth building has a more dissatisfied area.

Chapter 5 Conclusion

The highest bending resistance was 1284 96N/m² in specimen 3 with a density of 408 kg/m³. However, specimen 1 with 275 kg/m³ will have a better λ-value owing to low density. The thermal conductivity values from the test were not reliable for simulation due to the uneven surfaces of the wood wool slab specimen. Wood wool slab building consumes energy of 6,576 kWh compared to rammed earth 24,123 kWh and burnt bricks 17,922 kWh annually in case 10 kW. Therefore, it can be concluded that WWS has better energy performance than traditionally practiced rammed earth building materials, and commonly used burnt bricks in Bhutan. The thermal performance of wood wool slab building was better than rammed earth and burnt bricks when there was no heating system in a building. There were no uncomfortable hours below 0 °C for the WWS building whereas other building stretches to negative indoor temperatures. From this simulation results, WWS has proven to be better thermal-performing building materials compared to building materials such as rammed earth and burnt bricks. To prove further, WWS building has PMV at a range of -0.5 to +0.5 and PPD below 10 which are considered an acceptable thermal environment for general comfort according to ASHRAE 2004, but not in the case of rammed earth buildings. According to these findings, it can be concluded that WWS can be an alternative to substitute currently used building materials in Bhutan to make buildings energy-efficient and suitable indoor environments.

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APPENDIX

Building Physical Properties

The building elements construction for the simulation in DEROB-LTH is given in the Table.. below.

Table 1: Envelope details (from outside to inside) of a model

Building Elements	Materials	Thickness (mm)
Outdoor Wall	BWWS/SWWS/RE/BB	300
Boundary Wall	BWWS/SWWS/RE/BB	150
Ceiling	Cement plaster	25
	Super insulation	1000
	Reinforced concrete	150
	Cement plaster	25
Floor	Cement plaster	25
	Super insulation	1000
	Reinforced concrete	150
	Timber flooring	30
Window	Single glazing (glass)	6
Door	Hardwood	30

Construction Sets

These thermal properties of the materials are obtained from the standards or researched data(Clarke et al., 1990) except for the Bhutanese wood wool slab was original.

Table 2: Thermal properties of building materials

Materials	Conductivity (W/m·K)	Density (kg/m^3)	Specific Heat (J/kg·K)
Cement plaster	0.719	1648	920
Hardwood	0.17	800	1880
Timber flooring	0.14	650	1200
Burnt bricks	0.811	1820	878.4
Rammed earth	1.5	1800	700

Swedish wood wool slab	0.085	398	1130
Bhutanese wood wool slab			
Glass	0.90	2350	880

Internal gains

It includes the activity of people, lighting, and equipment loads. These gains are the factors affecting the indoor temperature of the building. To estimate the internal gains of an apartment, the following standards were used in the study.

Table 3: heating properties of the lamps

Data	Incandescent	Fluorescent	LED
Fraction Radiant	0.73	0.37	0
Fraction Visible	0.08	0.21	0.25
Return Air Fraction	0	0	0

Table 4: Metabolic rates of human activity

Activity	Activity level W/person schedule value	Activity level (W/m²)
Sleeping	72	40
Seated, quiet	108	60
Standing, relaxed	126	70
cooking	171-207	95-115
House cleaning	207-360	115-200
Walking (0.9 m/s)	207	115

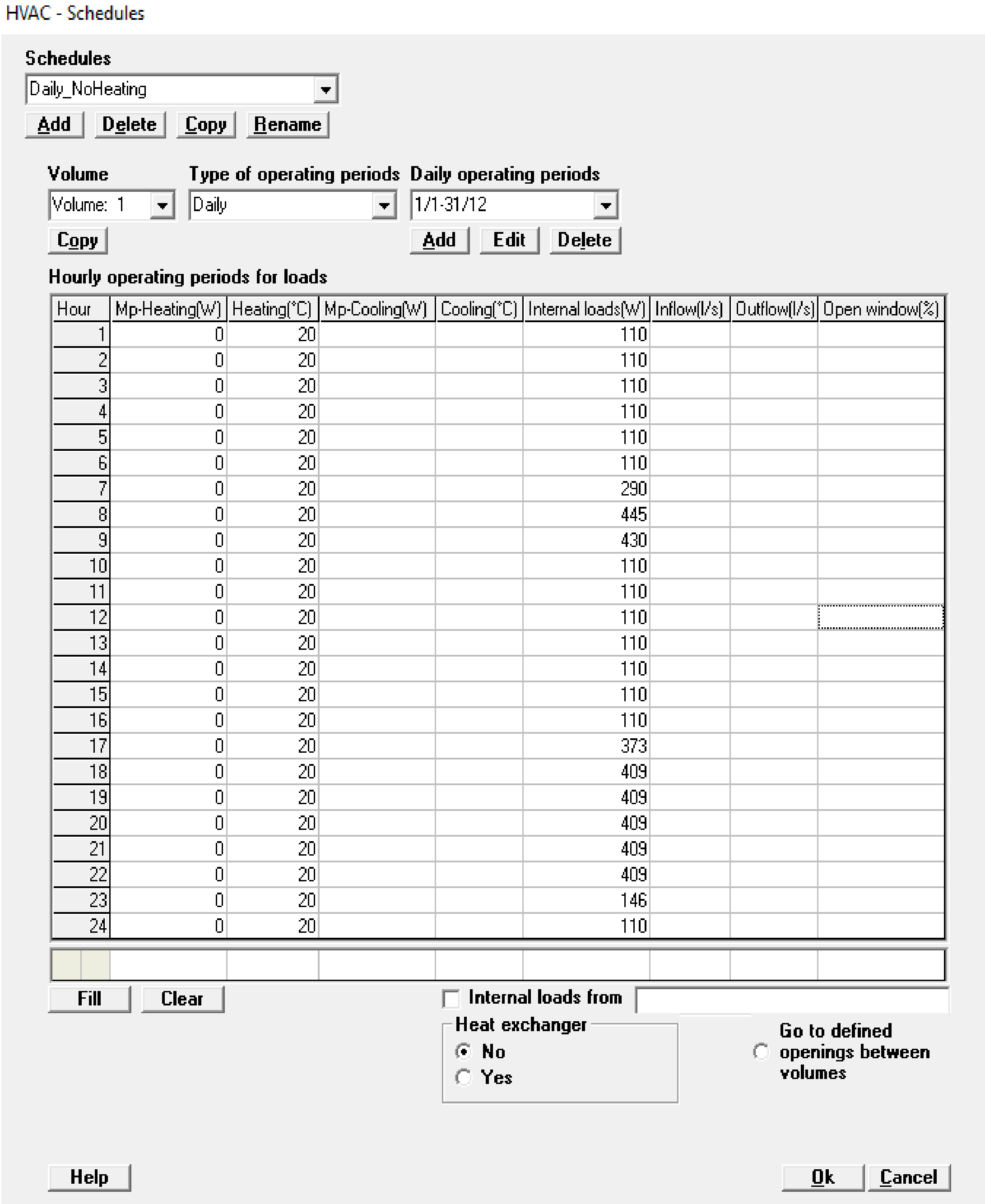
Table 5: Electrical loads of an apartment

Appliance	Power Rating (W)	Hours per day (hr)
LED Bulb	9	5
CPL Tube	2 x 36	4
Incandescent bulb	60	3

Water Boiler	1200	1
Rice Cooker	700	2
Refrigerator	110	24
Television	140	7

Schedule Sets

Proper scheduling is one main area through which we can be able to understand the heating and cooling energy demand in each building. Alongside this, the impact of ventilation and leakage through cracks and openings of the walls, doors, and windows.



Hour	Mp-Heating(W)	Heating(°C)	Mp-Cooling(W)	Cooling(°C)	Internal loads(W)	Inflow(l/s)	Outflow(l/s)	Open window(%)
1	0	20			110			
2	0	20			110			
3	0	20			110			
4	0	20			110			
5	0	20			110			
6	0	20			110			
7	0	20			290			
8	0	20			445			
9	0	20			430			
10	0	20			110			
11	0	20			110			
12	0	20			110			
13	0	20			110			
14	0	20			110			
15	0	20			110			
16	0	20			110			
17	0	20			373			
18	0	20			409			
19	0	20			409			
20	0	20			409			
21	0	20			409			
22	0	20			409			
23	0	20			146			
24	0	20			110			

Figure 1: Example of HVAC Schedule for simulation

The Calculation for Model Control

1. Transmission losses are at a steady-state.

		U- values (W/m², °C	Area (m²), Vol,1	Area (m²), Vol,2	Area (m²), Vol,3	Toral Area
1	Outdoor wall	1,484	26,16	26,16	45,36	97,68
2	Boundary wall	2,233	26,16	26,16	11,46	63,78
3	Window	5,88	2,6931	5,3862	5,8565	13,9358
4	Door	2,886	1,71	0	0	1,71
5	Roof	0,01	66,0096			
6	Floor	0,01	66,0096			

Wall	82,0342	1,484	121,7387528		
window	13,9358	5,88	81,942504		
door	1,71	2,886	4,93506		
roof	66,0096	0,01	0,660096		
floor	66,0096	0,01	0,660096		
			209,9365088		
			4198,730176	36780,87634	kWh °C

Figure 2: transmission losses calculation by hand

Simulation results without sun, internal loads, ventilation/infiltration			
Month	Heating-01 (kWh)	Heating-02 (kWh)	Heating-03 (kWh)
1	694,4	790,7	1160,6
2	629	716,1	1051,2
3	696,7	793,1	1164,3
4	674,2	767,5	1126,7
5	696,7	793,1	1164,3
6	674,2	767,5	1126,7
7	696,7	793,1	1164,3
8	696,7	793,1	1164,3
9	674,2	767,5	1126,7
10	696,7	793,1	1164,3
11	674,3	767,5	1126,7
12	696,7	793,1	1164,3
Total	8200,5	9335,4	13704,4
G.Total	31240,3	kWh	

Figure 3: Simulation result of steady-state

2. With constant ventilation

	0.3 l/s·m² constant ventilation		
Month	Heating-01 (kWh)	Heating-02 (kWh)	Heating-03 (kWh)
1	548	796,9	875,1
2	497,3	722,3	792,1
3	550,9	799,6	878,1
4	533,1	774,1	850,3
5	550,7	799,3	877,6
6	532,7	773,7	848,4
7	549,3	798,1	875,8
8	549,3	797,9	874,9
9	531,9	772,5	848,1
10	550,8	799,5	877,2
11	533	773,7	848,9
12	550,5	799,6	877,3
Total	6477,5	9407,2	10323,8
G.Total	26208,5		

	1.1 l/s·m² constant ventilation		
Month	Heating-01 (kWh)	Heating-02 (kWh)	Heating-03 (kWh)
1	600,8	837,7	945,2
2	547,2	760,8	852,2
3	606	841,5	946,6
4	586	815,3	918,1
5	605,2	840,4	944,6
6	584,9	814	911
7	599,9	836,1	937,9
8	600,1	835,3	934,7
9	581,7	809,4	909,8
10	605,5	841	942,9
11	586	813,9	912,5
12	604,3	841,2	943,4
Total	7107,6	9886,6	11098,9
G.Total	28093,1		

Difference in Heating demand 1884,6 kWh

Figure 4: Heating demand by constant air leakage

Yearly leakage 0,3 l/s/m²			
103956,7 m³			
Yearly leakage 1,1 l/s/m²			
385900,6 m³			
Difference in Volume of air leakage		281943,9 m³	
Heating energy demand	6766652,7	kJ	
	1879,6258	kWh	

Figure 5: heating energy demand by annual air leakage

3. With internal load

	Internal Loads in Watts		
Hours	Volume 1	Volume 2	Volume 3
1	110	0	288
2	110	0	288
3	110	0	288
4	110	0	288
5	110	0	288
6	110	0	288
7	290	36	2347
8	445	36	2143
9	430	0	772
10	110	0	0
11	110	0	0
12	110	0	0
13	110	0	0
14	110	0	0
15	110	0	0
16	110	0	0
17	373	0	0
18	409	36	1269
19	409	36	940
20	409	36	940
21	409	36	69
22	409	0	9
23	146	0	297
24	110	0	288
Total	5269	216	10802
Grand Total	16287	Watts	
	5944,755	kWh	

Figure 6: Total annual internal loads

	Without internal Loads					Without internal Loads		
Month	Heating-01 (kWh)	Heating-02 (kWh)	Heating-03 (kWh)		Month	Heating-01 (kWh)	Heating-02 (kWh)	Heating-03 (kWh)
1	1511,9	1686,3	1175,5		1	1351,2	1677,4	854,9
2	1405,6	1517	1066,2		2	1261,6	1508,9	776,4
3	1533,3	1681,5	1179,6		3	1374,1	1672,6	858,8
4	1527,1	1655,9	1145,3		4	1373,5	1647,3	834,7
5	1583,7	1703,2	1183,5		5	1425,1	1694,2	862,6
6	1520,3	1652,8	1143,9		6	1366,7	1644,1	833,4
7	1580,8	1708,1	1183,1		7	1422,4	1699,2	862,3
8	1552,3	1680,4	1179,7		8	1393	1671,5	858,9
9	1449,4	1609,1	1140,2		9	1294,2	1600,5	829,7
10	1558,5	1692,4	1181,9		10	1399,5	1683,4	861
11	1478,5	1612,6	1141,1		11	1323,7	1604	830,7
12	1548,7	1686,9	1181,1		12	1389,5	1678	860,3
Total	18250,1	19886,2	13901,1		Total	16374,5	19781,1	10123,7
G.Total	52037,4				G. Total	46279,3		
Difference in heating energy demand			5758,1	kWh				

Figure 7: Simulation result with and without internal loads

The Bending Resistance calculation

The moment in three-point-bending.

$$M = \frac{P * L}{4}$$

Where P is force (N) and L is span(m)

Moment resistance (for a rectangular beam)

$$W = \frac{b * h^2}{6}$$

Where b is breath and h is the height of the specimen

Stress (σ)

$$\sigma = \frac{M}{W}$$

<u>Specimen 1</u>

$$M = \frac{0.283\ kN * 0.68\ m}{4}$$

$$M = 0.048\ kN \cdot m$$

$$W = \frac{0.2\ m * (0.048\ \mathrm{m})^2}{6}$$

$$W = 7.68 * \ 10^{-5}\ \mathrm{m}^3$$

$$\sigma = \frac{0.048\ kN \cdot m}{7.68 * \ 10^{-5}\ \mathrm{m}^3}$$

$$\sigma = 625\ \mathrm{kN/m}^2$$

Density (ρ)

$$\rho = \frac{mass\ (m)}{Volume\ (V)}$$

$$V = L * B * H$$

$$V = 0.8\ m * 0.2\ m * 0.048\ m$$

$$V = 7.68 * 10^{-3}\ \mathrm{m}^3$$

$$m = 2.112\ kg$$

$$\rho = \frac{2.112\ kg}{7.68 * 10^{-3}\ \text{m}^3}$$

$$\rho = 225\ \text{kg/m}^3$$

Specimen 2

$$M = \frac{0.28\ kN * 0.68\ m}{4}$$

$$M = 0.0476\ kN \cdot m$$

$$W = \frac{0.2\ m * (0.048\ \text{m})^2}{6}$$

$$W = 7.68 *\ 10^{-5}\ \text{m}^3$$

$$\sigma = \frac{0.0476\ kN \cdot m}{7.68 *\ 10^{-5}\ \text{m}^3}$$

$$\sigma = 619.79\ \text{kN/m}^2$$

Density (ρ)

$$\rho = \frac{mass\ (m)}{Volume\ (V)}$$

$$V = L * B * H$$

$$V = 0.8\ m * 0.2\ m * 0.048\ m$$

$$V = 7.68 * 10^{-3}\ \text{m}^3$$

$$m = 3.172\ kg$$

$$\rho = \frac{2.112\ kg}{7.68 * 10^{-3}\ \text{m}^3}$$

$$\rho = 413\ \text{kg/m}^3$$

Specimen 3

$$M = \frac{0.58\ kN * 0.68\ m}{4}$$

$$M = 0.0986\ kN \cdot m$$

$$W = \frac{0.2\ m * (0.048\ \text{m})^2}{6}$$

$$W = 7.68 * 10^{-5}\ \text{m}^3$$

$$\sigma = \frac{0.0986\ kN \cdot m}{7.68 * 10^{-5}\ \text{m}^3}$$

$$\sigma = 1{,}283.85\ \text{kN/m}^2$$

Density (ρ)

$$\rho = \frac{mass\ (m)}{Volume\ (V)}$$

$$V = L * B * H$$

$$V = 0.8\ m * 0.2\ m * 0.048\ m$$

$$V = 7.68 * 10^{-3}\ \text{m}^3$$

$$m = 3.132\ kg$$

$$\rho = \frac{3.132\ kg}{7.68 * 10^{-3}\ \text{m}^3}$$

$$\rho = 407.8\ \text{kg/m}^3$$