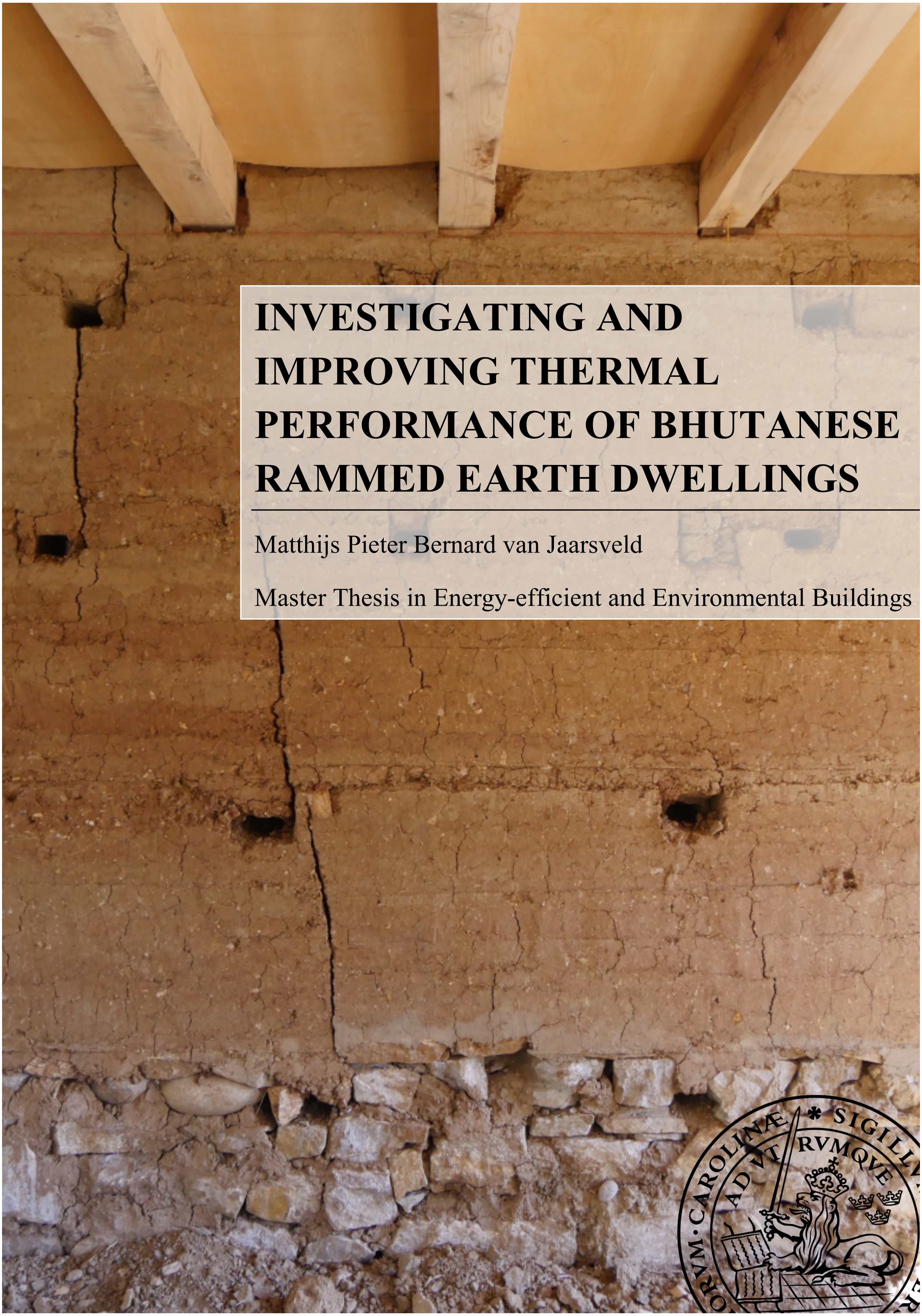

INVESTIGATING AND IMPROVING THERMAL PERFORMANCE OF BHUTANESE RAMMED EARTH DWELLINGS

Matthijs Pieter Bernard van Jaarsveld

Master Thesis in Energy-efficient and Environmental Buildings

Lund University

Lund University, with eight faculties and a number of research centres and specialized institutes, is the largest establishment for research and higher education in Scandinavia. The main part of the University is situated in the small city of Lund which has about 112 000 inhabitants. A number of departments for research and education are, however, located in Malmö. Lund University was founded in 1666 and has today a total staff of 6 000 employees and 47 000 students attending 280 degree programmes and 2 300 subject courses offered by 63 departments.

Master Program in Energy-efficient and Environmental Building Design

This international programme provides knowledge, skills and competencies within the area of energy-efficient and environmental building design in cold climates. The goal is to train highly skilled professionals, who will significantly contribute to and influence the design, building or renovation of energy-efficient buildings, taking into consideration the architecture and environment, the inhabitants' behaviour and needs, their health and comfort as well as the overall economy.

The degree project is the final part of the master programme leading to a Master of Science (120 credits) in Energy-efficient and Environmental Buildings.

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Abstract

Traditionally Bhutanese buildings are built with rammed earth. These buildings have low insulation values and lack thermal comfort resulting in sub-zero temperatures inside the homes in colder regions. Modern insulation materials in Bhutan are uncommon due to the lacking availability, and therefore, a local source of insulation material is needed to improve the living conditions. The worldwide use of natural and bio-based materials has increased over the past couple years, and the use of local natural materials has been investigated in this thesis to improve the insulation value and thermal comfort levels of Bhutanese rammed earth constructions. By adding the fibres straw, pine needles and rice husk, to the earth mixture in different percentages the thermal conductivity was decreased. The results of the different mixtures was used to quantify the improvement in operative temperature in unheated cases and energy use in heated cases.

The results of the Thermal Constants Analyser showed that the thermal conductivity was improved by 35 % by adding 8 % rice husk fibres to the earth mixture. However, the addition of fibres in an unheated case had insignificant impact on the operative temperature. In the heated cases the rammed earth wall construction only accounted for 5 % of the total energy loss and therefore the improvement in energy use of the building was also found insignificant.

When new buildings are constructed in Bhutan the following issues should be considered in order to build good buildings for the future:

1. Reduce infiltration;
2. Improve windows and doors;
3. Improve building materials.

In order to reach Western levels of indoor comfort, the rammed earth buildings need to be complemented with a proper insulation layer.

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Table of content

1 Introduction

Through a professor exchange in the Energy Efficient and Environmental Buildings Master's program, Lund University students were lectured by two Bhutanese professors and given an opportunity to (partially) conduct their research in the Kingdom of Bhutan.

1.1 Background and Motivation

In recent years there has been an increasing interest in using bio-based and natural materials such as earth, wood and other organic materials. These natural materials have lower embodied energy and thus have less impact on the environment in comparison to conventional materials such as concrete or clay fired bricks [1]. The main reduction of natural materials is due to lower embodied energy in the production and transportation phase of these materials[1].

Before the 1960's natural building materials such as earth and timber were common in the Kingdom of Bhutan. However, since the 1960's, the use of conventional materials such as concrete and clay fired bricks in Bhutan has increased [2]. This development has led to a loss of vernacular building techniques and both tangible and intangible heritage. One of the pillars of the ninth 5-year plan of the government was to preserve the tangible and intangible heritage [3]. In the past there were several programmes to preserve the cultural heritage such as the projects: 'Study on the Conservation of Rammed Earth Buildings in the Kingdom of Bhutan' and 'Improving Resilience to Seismic Risk'. One focus point of the second project was improving seismic resilience of Bhutanese traditional buildings for both existing and new rammed earth structures. Currently, a large part of Bhutanese dwellings consist of rammed earth constructions and new rammed earth buildings are still being built, indicating that there is a future for rammed earth buildings in Bhutan.

Besides the loss of cultural heritage, there is another downside to the adopted conventional building methods being: insufficient thermal performance. According to a study conducted in 1993 by the former Department of Works, Housing and Roads of the Royal Government of Bhutan [4], thermal performance and thermal comfort in modern Bhutanese buildings is exceptionally poor. This is a result of the building methods being adopted from India. According to Dujardin et al. [5], these building methods with low insulation properties are not suitable for the colder Bhutanese climate. A study by EY and DRE [6], shows a significant increase in energy loss though a brick wall versus that of a rammed earth wall. However, even though the thermal performance of a rammed earth wall is better, does not mean it is enough to achieve modern thermal comfort levels. As concluded by Minke [7] who stated: 'thermal insulation capacities of solid rammed earth walls using soil is not sufficient to provide levels of thermal insulation required in cold climates'.

One way to improve good indoor thermal comfort is by heating. Currently space heating in Bhutanese buildings is uncommon, a wood stove called '*bhukari*' usually located in the kitchen is the main and only source of heating. However, in the past couple of years, the number of electric heaters has been growing and, with it, the energy use for space heating [6]. The increasing amount of heating, combined with the traditional building technique that lacks thermal properties leads to unnecessary energy use in rammed earth buildings.

Therefore, by improving the thermal properties of rammed earth constructions, new rammed earth buildings could improve thermal comfort and reduce the energy use for space heating.

1.2 Aim and Objective

The aim of this thesis was to improve the thermal properties of traditional Bhutanese rammed earth walls and, with it, improve thermal comfort in traditional Bhutanese rammed earth dwellings.

The objective of this project was to investigate the construction methods in Bhutan. Furthermore, examine commonly used additives in earthen constructions and quantify the impact of local additives on the thermal and mechanical properties of Bhutanese rammed earth walls. Using a computational model of a reference building, simulate the effect on the operative temperature and the energy use for a heated and unheated building. These results were then compared to the results of a questionnaire filled in by students at the College for Science and Technology in Bhutan.

1.3 Research Approach

This research has partially taken place at Lund University in Lund, Sweden and partially at the Royal University of Bhutan - College of Science and Technology in Rinchending, Bhutan.

The main focus of this research was on improving the thermal performance and thermal comfort of a rammed earth building by adding natural additives to the construction material. The impact of these fibres on mechanical properties was also investigated.

This thesis contains both qualitative and quantitative research. A qualitative research analysis was done on: Bhutanese architecture, rammed earth building method and common additives in earthen constructions. The quantitative research consisted of the measurements on thermal conductivity both *in-situ,* during a field study, and in the laboratory. Furthermore, measurements on the mechanical properties of the in Bhutan made rammed earth samples. Finally, simulations of the energy performance and indoor thermal comfort were executed.

The rammed earth samples were made in Bhutan, with locally available natural materials. Compressive strength, tensile strength and elasticity was tested in Bhutan with a universal testing machine. The thermal conductivity was tested in Sweden using the Thermal Constants Analyser (TPS 2500 Hot Disk®), since this machine is only available in the laboratory in Lund.

With the results from the Thermal constants Analyser, the effect on energy performance of a traditional Bhutanese building was simulated using the open source simulation engine EnergyPlus [8]. EnergyPlus was used for measuring the impact on thermal comfort. To compare the results a survey that was filled in by the students of the College of Science and Technology in Bhutan. The questions in this survey were related to their perception of indoor thermal comfort, related to their home built with natural materials such as: earth, stone, timber and bamboo.

1.4 Scope

There are multiple earthen constructions techniques used in Bhutanese buildings, this thesis focussed only on improving rammed earth constructions of residential buildings constructed in traditional Bhutanese style. Thermal conductivity of the construction was improved by solely adding natural additives to the earth mix.

1.5 Structure of the Report

The first chapter is split into several sections and describes the background of this thesis, the aim and goals, the research approach, the scope and the structure of the report. Chapter two provides geographical background information on the Kingdom of Bhutan and its vernacular architecture. Furthermore, it provides information regarding different earth building techniques. The literature review delves deeper into the use of additives in earth and rammed earth constructions, as well as thermal comfort in rammed earth dwellings. This information was needed to determine the inputs for the tests that were done and these are discussed in the fourth chapter 'Materials and Methods'. The fifth chapter 'Properties of the Reference Building' describes the reference building and the properties that were used for the energy and thermal comfort model. In the sixth chapter the results are presented and these are discussed in the seventh chapter, chapter 8 entails the conclusion. All figures presented are own figures, unless stated otherwise.

2 Background

This section provides geographical and architectural background information on the Kingdom of Bhutan. The architectural section is divided in two sections; monumental architecture and residential buildings. The monumental buildings are:

- Temples (*lhakhangs*);
- Monasteries (*goenpas*);
- Fortresses (*dzongs*);
- Stupas (*choeten*), Buddhist burial mounds.

Subsequently the building type central to this thesis, the traditional Bhutanese residential dwelling (*yue chim*), its building techniques and construction types, will be introduced.

2.1 Geographical Background the Kingdom of Bhutan

Bhutan is a landlocked country located in the Eastern Himalayas. It shares its borders with Tibet in the north and north-west and the remainder with India. Bhutan is a relatively small country with roughly 38 500 km² of surface area and approximately 800 000 inhabitants [9]. The climate in Bhutan can be divided in to three climate zones. The first being sub-tropical in the south with an elevation starting at 160 metres, the second is its central region with a temperate climate and the third an alpine climate in the north with elevations up to 7 000 metres above sea level [4]. Figure 1, shows the spatial temperature distribution with the warmer temperatures in the south and colder climate in the north [10].

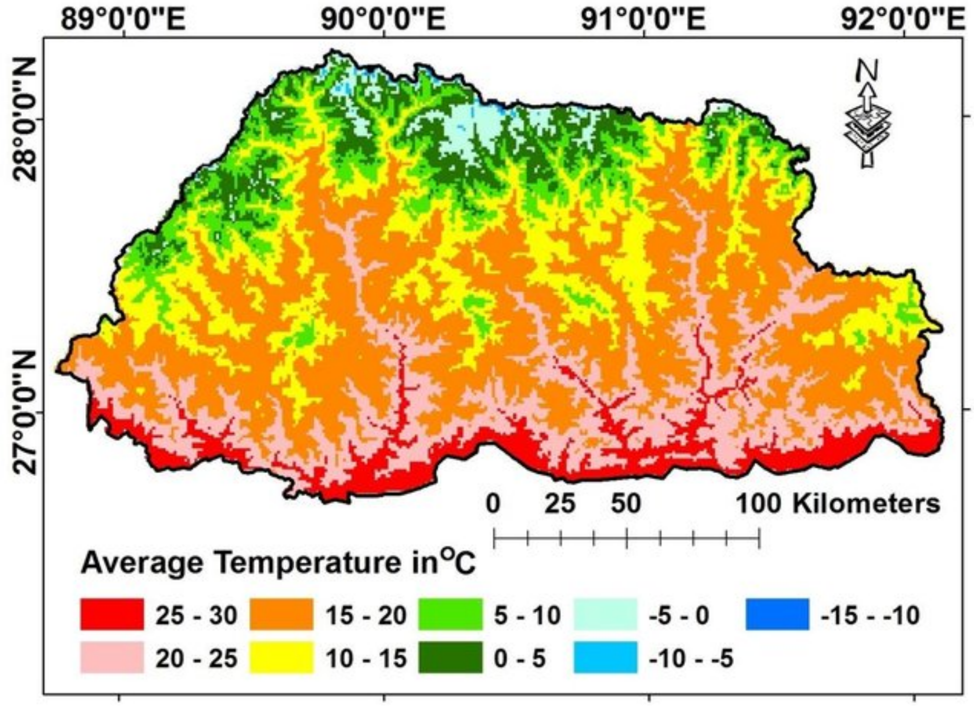

Figure 1: Spatial temperature distribution in Bhutan

Source: Adapted from [10].

2.2 Monumental Architectural

Bhutan is well-known for its impressive and unique architecture with large buildings with distinctive features such as tapered whitewashed walls, top heavy wooden upper levels and large overhanging gable roofs.

Figure 2: Paro Taktsang Monastery; built in 1692.

Figure 2 shows the most sacred and famous Bhutanese *goempa*, called *Taktsang* monastery, also known as *Tiger's Nest* [11]. Within a *Goempa* the temple (*Lhakhang*) is divided from the monks' their living quarters by a courtyard [12]. According to the Bhutan Architecture Guidelines [12] *Lhakhangs,* serve not only a religious function but also a social, cultural and gathering function within the communities. A Lhakhang is often a stand-alone building in a town or village or it is located within a *Goempa*.

Dzongs are present in each *Dzongkhag* (district) and are used for monastic purposes and as local government administrative buildings. Often overlooking a valley, the location of the *Dzongs* usually has a strategic position, reflecting its former military significance. The layout is typically split in two, with the governmental offices on one side and the living quarters and religious areas for the monks on the other.

It is said that *Dzongs* have been built according to the vision of *Dzong* architect, without any drawings [12]. The construction of a typical *Dzong* has large whitewashed tapered earth or stone masonry walls. With decorative architectural elements made from wood. Figure 3 shows *Simtokha Dzong*, the first historic *Dzong* built in 1629 by Zhabdrung Ngawang Namgyal that is still in use today.

Figure 3: Simtokha Dzong; built in 1629.

Choetens or stupas (meaning: ‘pile’ in Sanskrit) are religious structures either containing relics from Buddha, monks or nuns, or are placed over buried offerings. Throughout Bhutan you can find Bhutanese, Tibetan and Nepalese *choetens*, which all have their distinctive shapes, with typical Bhutanese *choetens* being square shaped [3]. Figure 4 shows a Bhutanese *choeten* on the left and on the right the Thimphu memorial, this is a Tibetan style *choeten*. The round shape represents Buddha who is sitting on a square base representing a throne.

Figure 4: Bhutanese Style choeten (left) and Tibetan style choeten; Thimphu Memorial built in 1974 (right).

2.3 Residential Buildings

According to the 2017 Bhutanese Livings Standards Survey [13], there are roughly 164 000 residential buildings in Bhutan. Of these buildings, 35.9 % have walls made out of earth or stone, 24.9 % out of cement-bounded bricks or stone-walls, 13.9 % have concrete walls and 12.9 % have timber walls. Of the Bhutanese population 66 % live in rural areas and 34 % in urban areas [13].

The construction types mentioned above are mainly separated based on local climate. In the lower altitudes in the south of Bhutan, the buildings were traditionally built out of thatched bamboo [11]. This type of construction allows natural ventilation and still provides privacy in hot and humid regions [14]. In the central and eastern region stone buildings are common, and in the west mudbricks and rammed earth. In the higher altitudes in the North, stone structures can be found and occasionally a traditional yak hair tent [11][12].

Bhutanese rammed earth dwellings are typically three stories high. The bottom two stories are built with thick earth walls. The top floor is only partially built out of earth, as the façade, is built with a wooden architectural feature. This feature is called a *rabsel.* The wooden feature (sometimes) extends over the ground floor construction and has large windows facing the valley. A typical rammed earth dwelling with a *rabsel* is shown in Figure 5 [12].

The floorplan is described by the Architecture Guidelines [12] as practical and suiting the local needs. In a typical Bhutanese rammed earth dwelling the ground floor was traditionally used for livestock and storage of feed for the livestock. The first floor was also used for storage, mainly for produce from the farm, with an air drying room for curing meats and vegetables. The second floor locates the kitchen, the living room, the prayer room and the bedroom(s). The attic is an open and airy attic (which is not part of the thermal envelope), which is also used for drying produce from the farm [12].

Figure 5: Typical Rammed Earth Dwelling, with on the second floor a rabsel with earth infills [12].

2.3.1 Bhutanese Earth Building Constructions

This section will describe the different construction types and earth building techniques seen in vernacular Bhutanese buildings, starting with the foundation working up to the flying roof construction.

2.3.1.1 Foundation and Floor Constructions

Foundations and the plinth of earth buildings were usually built with large stones and clay mortar. Nowadays a cement mortar is more common, as seen in Figure 6. A solid foundation and plinth is necessary to prevent moisture movement through capillary suction [15]. Figure 6 also shows a weathered and a newly built rammed earth construction.

Figure 6: Rammed earth wall on traditional(left) and modern(right) plinth

Ground floors are usually earthen floors. Due to the function of the rooms (shelter for livestock and storage of fodder) there is no need for a different type of flooring. Floors in the living area are either wooden floors or earth floors. In case of internal floors or roof constructions, bamboo or timber and straw is placed on the cross beams and covered with wood or clay earth. Figure 7 shows the bottom view of a floor or flat roof construction, the straw in between the bamboo is clearly visible. The function of the straw is to prevent the earth from falling through, or reduce infiltration.

Figure 7: Bottom view of traditional intermediate earth floor construction.

2.3.1.2 Wall Constructions

In Bhutan, several building techniques for earth wall constructions are applied. External earth walls in Bhutan are either built with rammed earth or mudbricks. In Figure 8 a building with a combination of these two techniques is shown with rammed earth in the bottom half and mudbricks in the top half of the ground floor.

Rammed earth constructions are made by compacting layers of earth inside a formwork, the different layers of earth or 'flights' are clearly visible. A more detailed description of how to build rammed earth walls will follow in section 2.3.2.

The second earth construction comprises of mudbricks. Mudbricks are made with a mixture of earth, sand, water and occasionally straw, this mixture is also known as cob. This mixture is pushed in a mould and the bricks are left to dry in the sun. The advantage of mudbricks is that these can be easily stacked and also be used for creating arches [16].

Figure 8: A Bhutanese building with a combination of earth building techniques

There is also a third technique known as wattle and daub, this technique is mainly used for interior walls. Wattle and daub consists of a woven lattice made with wood or bamboo, which are then covered with a cob-like mixture. This method tends to use more water due to the fact that the material needs to be pushed into the woven lattice. The infills in the *rabsel* construction (called *shamig*) are discussed in section 2.3.1.3 [12].

Surface treatment of (rammed) earth buildings often consist of a whitewash, yet this method is not applied on all buildings. During the field study it was observed, that there was a layer of cement plaster added to the external surface of the façade.

2.3.1.3 Facade Constructions

The top floor of a typical vernacular Bhutanese residential building has a wooden element called *rabsel*. This element also houses some architectural features typical for Bhutan. The *rabsel* has a cluster of several small single pane windows and is surrounded by a grid with wooden or earth infills. The earth infills are called *shamig* and the wooden panel infills are called *soma* [12]. On Figure 9 the windows and earth panels are visible.

Figure 9: Bhutanese dwelling with earth panel infills

2.3.1.4 Roof Constructions

The type of roof construction used in Bhutanese buildings depends on the status of the building. In general, it consists of a light construction above the building, this is called a 'flying roof'. The different types of roof designs are:

- *Jabzhi*: multi-layered square hip gable roof for important buildings;
- *Jamthok*: gable or partially layered (hip) gable roof for residential buildings;
- *Drangim*. layered gable roof over the full length of the residential building.

The purpose of the flying roof is to create an attic space with high amounts of ventilation and protection against the elements, for example heavy rain during monsoon season [12]. The attic in residential buildings is used for storage and drying food from the land and for storage of fodder for the livestock. This flying roof construction is not part of the thermal envelope. The thermal envelope comprises of an earth floor construction as mentioned in the floor section.

Traditional roofing materials are thatch, wood and slate tiles; nowadays the common roofing material used is congregated metal sheets which are used on 95 % of the roofs [13].

2.3.2 Construction of Rammed Earth Walls

To construct a rammed earth wall, earth is compacted with a tamper in between a formwork, creating layers of roughly 200 mm high and up to 3 000 mm long, the formwork is then moved to create the next layer or 'flight' [17]. For rammed earth dwellings the walls are generally between 600 mm and 800 mm thick and are not tapered [12]. In Figure 10 the closed formwork and the tampers are visible, as well as the structure keeping up the formwork. This structure penetrates the wall and gives it the distinctive holes as seen in Figure 5, Figure 6 and Figure 8. To reduce the infiltration, these holes need to be filled after construction.

Figure 10: Three women working on a rammed earth building

The earth extracted from the ground suitable for a rammed earth construction needs to be free from organic matter and larger particles. According to Minke [7] particularly gravelly mountainous loam is very suitable for rammed earth constructions. The suitability of a mixture for a rammed earth construction can be tested in the field with three cohesion tests:

Ball test: The ball test is done with 5 balls with 20 mm diameter and left to dry in the sun for 48 hours. Then the balls are compressed in between the thumb and index finger, if the balls don't break the clay content is sufficient [15].

Ribbon test: A ribbon is pushed over the edge of a surface, the length at which the sample breaks indicates if the sample is suitable for a rammed earth construction [7].

Roll test: A ball of soil is moistened until a 10 mm steel rebar sinks 20 mm into the ball. This ball is then rolled into a 200 mm long roll with a diameter of 25 mm. This roll is then pushed over the edge of a table and depending on the length that breaks off, the amount of clay is sufficient. If it breaks between 80 mm and 120 mm the amount of clay is sufficient. If the clay content is too high, sand can be mixed in, if the clay content is too low a new source of clay earth needs to be found [9].

If the loam is found to be suitable, its optimum moisture content (OMC) needs to be determined when using the loam. At the OMC the particles in the loam mix will have the highest compaction and dry density. The ‘drop test’ is used to find the optimum moisture content in the mixture needed for making a rammed earth wall [18].

Nevertheless, according to Minke [7], field tests show large variations in mechanical properties compared to a lab environment, making the material testing in a controlled environment preferable.

3 Literature Review

3.1 Building Codes and Standards

The current ‘Bhutan Building Rules’ sets rules for the permit process, spatial, architectural and structural requirements. The architectural design requirements refer to the ‘Guidelines on Traditional Architecture’. The structural requirements are standards from India. To this date there are no building codes in Bhutan related to energy efficiency in buildings.

The 1998 Indian Standard IS 13 827 Improving Earthquake Resistance of Earthen Buildings - Guidelines is used for construction of earthen buildings in Bhutan. Besides the Indian Standard there are also other standards related to earth buildings used in other countries. For example:

- HB 195 – 2002 : The Australian Earth Building Handbook
- NZS 4 297 : Engineering design of earth buildings (1998)
- HS 983:2014 : Rammed earth structures – Code of practice (2014)

A comparison by Ciancio et al. [19] on several earth building standards and guidelines plus the data from the more recent HS 983:2014, either mandate or advise a compressive strength ranging from 1.0 N/mm² to 2.0 N/mm² and a tensile strength ranging from 0.25 N/mm² to 0.5 N/mm² [18]. The IS 13 827:1993 which is used as a guideline in Bhutan states that a minimum compressive strength for soil of 1.2 N/mm^2 is ‘desirable’ [15].

3.2 Earth as a Building Material

To build a rammed earth wall soil is needed. The top two layers of the earth’s crust are respectively topsoil and subsoil. Topsoil has more nutrients and organic matter than subsoil and topsoil is therefore more suitable for agriculture. Subsoil is the type of soil that is most suitable for earth constructions. Subsoil is found from 350 mm to 750 mm below the surface [1][7].

Loam, the material used for earth buildings is a mixture of the aggregates: gravel, sand, silt, and clay, and for to constructing a rammed earth wall several ratios can be used. Ciancio et al. [19], has summarized the desired material composition as stated in several guidelines. This summary, including the more recent material requirement as stated in the HS 983:2014 (Southern African Development Community Cooperation in Standardization’s regional standard) [18], results in the following range of aggregates:

- Gravel and sand : 45 % to 80 %
- Silt : 10 % to 30 %
- Clay : 5 % to 20 %

Within the desired bandwidth the mechanical properties of the material is sufficient. Each aggregate has a specific function in this; sand (2.0 mm to 0.06 mm) and silt (0.06 mm to 0.002 mm) in the loam mixture is the aggregate and the binding forces of these materials depend on the friction between the different particles. Clay (smaller than 0.002 mm) binds the mixture together with its structural bonding properties [7][20].

Not all loam is the same, it can differ in density but also in the additives used in the loam. To differentiate between different types of loam Minke [7] states that the expired German standard DIN 18 951 provided a definition. A mixture above 1 200 kg/m³ is called loam, below 1 200 kg/m³ it is called lightweight loam. Depending on the additive in the loam, for example straw, the name of the additive is used e.g. straw loam or lightweight straw loam. The following section will further discuss different additives that can be used in earth buildings.

3.2.1 Additives in Earthen Constructions

To enhance the thermal and mechanical properties of the earthen constructions additives can be added, this has been done for over thousands of years [7]. Several studies regarding additives in loam constructions have been found. The amount of studies regarding the use of additives in specifically rammed earth constructions was little. This was also concluded in a study by Laborel-Prénom et al. [21] who stated: 'These [rammed earth, cob, wattle and daub] traditional earth construction techniques are very little studied in the literature and few studied found were not very relevant'. The following sections therefore describe additives in earthen constructions in general. The additives will be split in two types: natural and manufactured additives.

3.2.2 Natural Additives

Natural additives can be made from plants or animals. Plant additives have been grouped by Laborel-Prénom et al. [21] based on 50 studies, into eight categories: cereal straws (17/50), wood aggregates (10/50), bast fibres (8/50), palm tree fibres (7/50), waste & residue (7/50), leaf fibres (5/50), aquatic plants and chips (4/50) and sheep wool (2/50) [21]. Straw, wood aggregates and the bast, palm and leaf fibres, waste & residue will be further discussed, as these additives are easily available in Bhutan, sheep's wool and aquatic plants are not.

Straw is a waste material that has little nutritional value for livestock and is therefore a suitable material to use as a building material. The use of straw is common in cob and adobe buildings to enhance the mechanical properties as well as improve the thermal conductivity of the construction. Straw can be any type of cereal straw. The length of the straw in earthen constructions according to the seventeen studies ranges from 0 mm to 300 mm[21]. Minke [7] describes the maximum length to be no longer than the size of the construction.

The amount of straw used in the seventeen studies ranges from 1 % to 3 % by weight [21]. The use of straw is also recommended by the Indian standard; the function of straw is fissure control. This is mentioned in a chapter regarding specifically rammed earth constructions. The maximum amount is one fourth of the volume of the earth and water mixture[15].

Wood aggregates are a waste product of woodworking consisting of wood fibres, wood chips, sawdust and even fine branches. The size of these particles range from 3 mm to 20 mm. Adding wood aggregates is more common in compressed earth bricks and the amount of aggregates ranges from 0 % to 10 % by weight[21].

Waste and residues consist of e.g. 'millet, cotton, tea, tobacco, cassava peels or grass' [21].

Fibres consist of bast, palm or leaf fibres, being hemp, flax, jute, coconut-, rice- or corn husk. The differentiation between these fibres is based on the aspect ratio, this will be discussed in the next section. The bast, palm or leaf fibres range from 0 mm to 85 mm and are added by weight ranging from 0 % to 5 %. There are however some exceptions, sisal leaf fibres with lengths up to 1 600 mm have been used as well as hemp mass percentages up to 22 % [21].

The aspect ratio is the ratio between the length and the diameter of the additive. The aspect ratio influences the mechanical properties. Danso et al. [22], their study showed that for particular additives increasing aspect ratio resulted in increasing mechanical strength, and with other additives a peak was reached thereafter the strength decreased, the latter was also concluded by Sangma et al. with the addition of coir fibre [23].

Not only plant aggregates and fibres have been added to earth, other additives consist of fats and oils e.g. flaxseed oil have been used to improve the moisture resistance and in some admixtures increased the mechanical strength of natural constructions [7][24][25].

3.2.2.1 Manufactured Additives

Manufactured additives are for example cement and lime, which are used to enhance the mechanical properties of earth construction materials. The amount of cement and lime used ranges from 1 % to 15 % by weight. Depending on the percentage and type of clay in the clay earth mixture more cement or lime is needed to bind the sand and silt particles in the clay earth blend [7]. According to the Australian building standards above 15 % by weight the construction is not recognised as an earthen construction [26].

There have also been other additives used in combination with lime. Lime needs water and a pozzolanic material to create cementitious properties. There are several additives (with a natural source) available that have pozzolanic properties. Multiple studies [27][28][29] have been conducted of which two add rice husk ash and a single study that uses ash from bamboo leaves earth to enchase these pozzolanic properties. Another source of pozzolanic material is fly ash from for instance (coal) thermal electric plants [30].

Other man-made additives for example bitumen are used to make the earthen constructions more water resistant [31]. Furthermore, there are also other fibres or waste materials used e.g. polypropylene or marine plastic [30][32].

This research aims to improve the thermal properties without the use of man-made additive. Therefore, the effects on material properties of man-made additives will not be further discussed.

3.2.3 Available Additives in Bhutan

Bhutan has a large coverage of forests, and in 2010 the forest coverage was roughly 70 %, the minimum percentage of coverage mandated by the government is 60 % [33]. Therefore, wood and the fibres of trees should also be readily available. In the Paro and Thimphu region, the climate is moderate to cold, the trees available are mainly pine trees. Furthermore, the woodworking industry produces wood waste in the form of shavings, as was witnessed during the field study.

Agriculture plays an important role in Bhutan. According to a study of the Ministry of Agriculture and Forest [34], 69 % of the populations livelihood depends on agriculture and the cultivated crops are: rice, maize, wheat, barley, buckwheat and millets [33]. This means that cereal and rice straw should be readily available. Furthermore, the rice husk, a waste material of milling the rice should be available at local rice mills.

3.3 Properties of Earth Constructions

The following sections show the correlation between the material its thermal and mechanical properties and the density. Due to the large amount of definitions for density found in the literature, two definitions will be clarified, wet and dry density. The following figure by McCartey et al. [35] illustrates the composition of a loam sample, the sample comprises of solid matter, water and air.

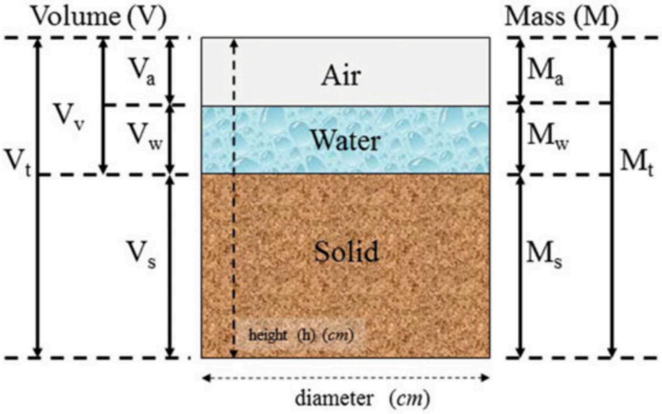

Figure 11: Relationship of volume and mass of a soil sample separated into capillary (water), non-capillary (air) pores, and solid mass. V = volume, M = mass, a = air, w = water, s = solid, v = voids, t = total

Source: Adapted from[35]

The first definition is dry bulk density, this is the ratio between the dry weight (Ms) of an earth mixture and the volume of the material including voids (Vt). The second definition is the wet bulk density, the ratio between the wet weight (Mt) of a mixture and the volume (Vt) of the of the material including voids.

According to Bui et al. [36], this wet weight of rammed earth samples includes a moisture content between 11 % and 2 % by weight. These percentages represent respectively the moisture content after manufacturing and at atmospheric conditions. The dry density can be determined when a sample is dried in the oven at 105 °C [35].

3.3.1 Thermal Properties of Earth Constructions

Specifically related to the thermal conductivity of a traditional Bhutanese rammed earth wall there is one field study conducted by Jentsch et al. [37]. The measured rammed earth building had a thermal conductivity of 1.10 W / (m × K), the dry bulk density of this specific construction was estimated at 2 000 kg/m³.

Furthermore, the study by Laborel-Prénom et al. [18] gathered the available thermal conductivities of the different earth building materials with the use of plant aggregates as seen in Figure 12. Besides these specific studies there are also some generic thermal conductivity values stated in DIN 4 108-4:2017-03 [38]. These values however, are similar to the values in Figure 12.

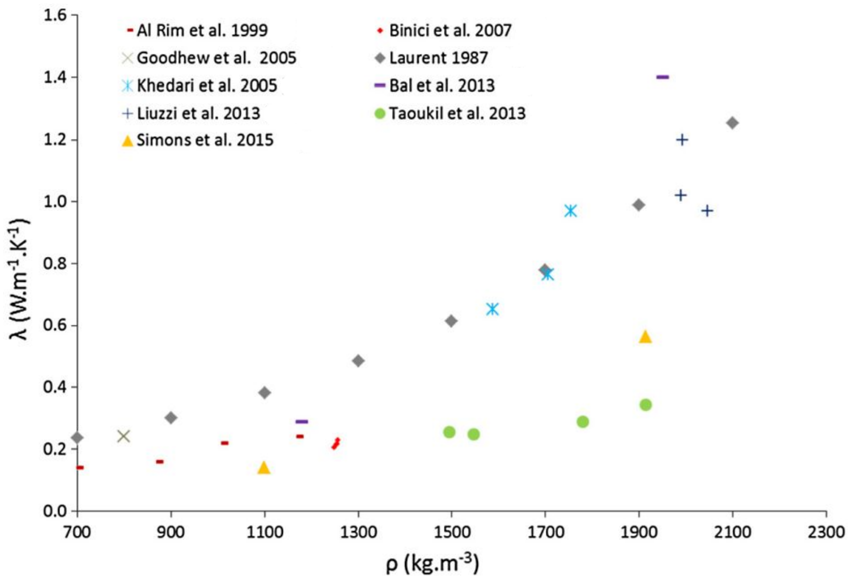

Figure 12: Thermal conductivity versus (dry) bulk density; figure from a review study on aggregates and fibres

Source: Adapted from [21]

The study however doesn't state the moisture content at which the different measurements have been conducted. The moisture content in building materials is dynamic and varies over the year. A study conducted by Hall and Allinson [39], states that: 'there is a linear increase between the saturation ratio and the thermal conductivity', meaning that an increasing moisture content results in an increasing thermal conductivity.

Not only does a high relative humidity have a negative impact on the thermal conductivity. According to Laborel-Prénom et al. [21], a high relative humidity (above 70 %) can: 'encourage microbial activity inside the material and thus accelerate biodegradation of the plant material'. Furthermore, Viitanen [40] stated the favourable conditions for several types of fungi start at 75 % RH with a temperature range between - 5 °C and 50 °C. Besides fungi, insects also affect organic material, the favourable conditions for insects start at 65 % RH and a temperature range between 5 °C and 50 °C. Damage of the construction however, only occurs after repeated or prolonged periods of time within the favourable conditions [40].

These favourable conditions can be the result of several factors. According to Viitanen [40], these factors include: 'water leakage, convection of damp air and moisture condensation, rising damp from the ground and moisture accumulation in the structure.

3.3.2 Mechanical Properties of Earth Constructions

Besides the effect on the thermal properties, the use of additives also influences the mechanical properties. A study conducted on adobe bricks by Calatan et al. [41] looked at the effect on both thermal conductivity and mechanical properties of adding hemp fibres and straw fibres (by volume) to mudbricks (*adobe*). This study showed the relationship between thermal conductivity, compression strength and dry bulk density. In this case the compressive strength decreased with an increasing percentage of additives.

The review study conducted by Laborel-Prénom et al. [21] found that in eight cases the compressive strength increased and in eleven cases the compressive strength decreased, by adding additives. This was caused by 'the effect of aggregate or fibre on compressive strength depends on the type of plant aggregate or fibre, the particle geometry, and the soil composition' [21]. Furthermore, increasing the amount of additives resulted in a decreasing elasticity. Finally, an increasing additive content resulted in an increasing tensile strength; in favour of fibres over aggregates.

A study by Miccoli et al. [42] summarized the mechanical properties of *in situ* measured mudbricks, rammed earth and cob, with a focus on the properties of rammed earth. The findings are visible in Table 1. This table shows that the mechanical properties vary with similar densities, this is due to the different compositions of the loam and the type of clay, as mentioned in the previous section and section 3.2.

Table 1: Summary of material properties for earthen materials in the literature. (n.d. = not determined)

Material	Dry Bulk density / kg / m³	Compressive strength / N / mm²	Tensile strength / N / mm²	Young's modulus / N / mm²
Mudbrick	1 870	2.15	0.021	315
Rammed earth	n.d.	0.60 - 0.70	n.d.	60
	1 700 - 2 400	1.5 - 4.0	n.d.	750
	1 763 - 2 027	0.62 - 0.97	n.d.	60 - 70
	1 800	1.0	n.d.	90 - 105
	1 850	3.88	n.d.	205
	1 850	2.46	n.d.	160
	1 870 - 2 170	1.80 - 2.00	n.d.	n.d.
	2 020 - 2 160	0.75 - 1.46	n.d.	n.d.
	2 100 - 2 300	2.40 - 3.00	n.d.	650
Cob	1 400 - 1 700	0.45 - 1.40	0.09 - 0.34	170 - 335

Source: Adapted from [42]

Besides the previous *in-situ* measurement there is also a research specific to Bhutanese buildings. The compressive strength of Bhutanese rammed earth buildings has been tested by the Japanese National Research Institute for Cultural Properties and the Bhutanese Department of Culture, Ministry of Home and Cultural Affairs. The study [43], shows that in many cases the guidelines related to compressive strength are not met. In the study cylindrical samples were extracted from 38 rammed earth buildings and the wet bulk density and the compressive strength was measured. Figure 13 shows the results of this study. The results are distributed in two areas: the first with a density of 1 700 kg/m³ to 1 800 kg/m³ have a compressive strength of 0.5 N/mm² to 0.9 N/mm², the second with a density of 1 900 kg/m³ to 2 000 kg/m³ and a compressive strength of 1.4 N/mm² to 1.7 N/mm². The figure shows that a large amount of buildings doesn't reach 1.2 N/mm² as stated in the Indian Standard 13 827 [15]. However, the minimum wall thickness stated in the Indian Standard is 380 mm, this is the case for mudbricks. Specific requirements for rammed earth walls, that are typically 600 mm to 800 mm, are not mentioned.

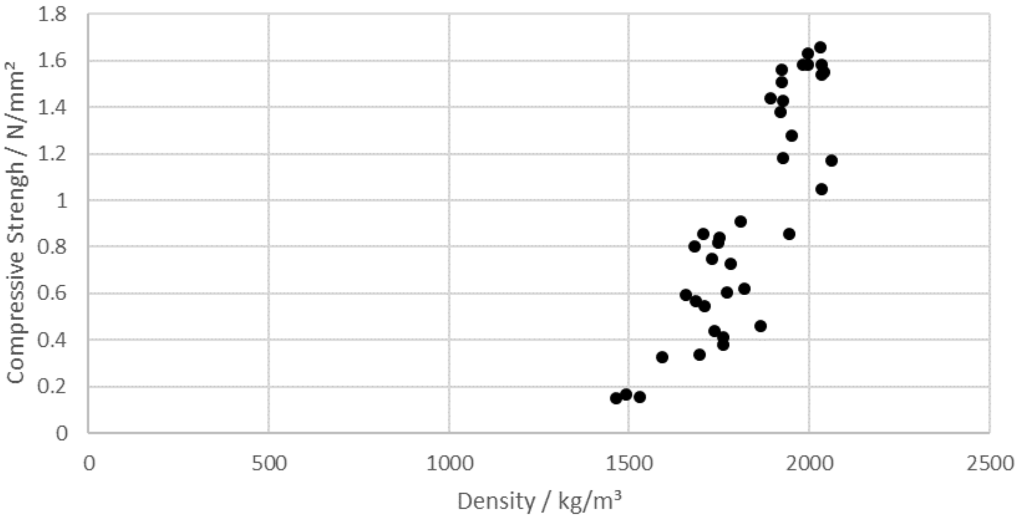

Figure 13: In situ compressive strength measurements of Bhutanese rammed earth buildings

3.4 Thermal Comfort Levels in Rammed Earth Dwellings

A study conducted by Jentsch et al. [37] measured the interior temperature of a traditional unheated Bhutanese rammed earth dwelling during October 2015. The results show a 3-day mean indoor temperature of 15.2 °C and a minimum of 13.4 °C. This occurred during a day with a diurnal temperature variation of 17 °C. The lowest temperature was slightly above 5 °C and the maximum temperature slightly above 22 °C.

Furthermore, one study by Dong et al. [44] related to thermal comfort in moderate to cold climates was found. This was a free running (c.q. unconditioned) Australian rammed earth building simulation. In this specific study one of the studied locations was Ballarat, Australia. In this study the outdoor temperature in a typical winter week fluctuated between roughly 4 °C and 10 °C, during this week the indoor temperature fluctuated between 10 °C and roughly 12.5 °C. The Bhutanese climate in the Paro and Thimphu valley however, is a lot colder reaching temperatures as low as minus 20 °C according to the EnergyPlus weather file, received from the College of Science and Technology.

4 Materials And Methods

To measure the impact of the additives on the thermal and mechanical properties several test rigs were used in the laboratory.

4.1 Gathering and Mixing Earth with Additives

The study was conducted with seven different earth mixtures including a reference sample. The amount of earth needed for all the samples was estimated, the earth was collected and mixed thoroughly. The earth blend used for the mixtures was extracted from the ground on the campus of the College for Science and Technology of the Royal University of Bhutan. After removing large particles by hand, properties were tested according to the 'roll test' to determine if the mixture had enough clay as per HS 983:2014 [18]. The batches were weighed and additives were added in various percentages. The mixing of the batches with additive was done by hand.

The type of additive was determined by the availability in the Thimphu valley, and on the found common additives in earth buildings according to the literature. Straw was available at a farm, pine needles from the trees and rice husk from a local rice mill. The percentage and size of the additive was determined based on literature and empirical evidence. Figure 14 shows the fibres that were collected.

Figure 14: Used fibres, from left to right: straw, pine and raw rice husk

The study by Hegedis et al. [45] showed that the highest compressive strength was achieved at 1 % straw by weight, this was then chosen to be the base case. To further improve thermal properties 3 % and 6 % was mixed. However, these earth and straw mixes were not able to adhere or bind together. A 2 % mix did succeed; however, the mixing process was difficult where many 'knots' of straw where formed especially between the different layers of earth in the 'test' mould as visible in Figure 15. This resulted in the different layers in the specimen not adhering. The length of the fibre in the first mixes was according to the literature, not longer than the formwork, in this case being just under the length of the mould, 50 mm, 100, mm and 150, mm. A solution to this was chopping the fibres with a large knife to shorter pieces of maximum 20 millimetres, to prevent 'knots' from forming resulting in a more homogenous mixture used for the sample (Figure 15).

Figure 15: Two samples with 2 % straw by weight, 100 mm fibres(left), 20 mm fibres (right)

A study by Shamra et al. [46] showed that 1 % by weight of pine needle gave the highest improvement in compressive strength, this was again used as the base case. The same challenges as with the straw were encountered; 'knots' of pine needles formed during mixing creating an inhomogeneous mixture in the moulds. This again was solved by chopping the fibres by hand into shorter pieces up to maximum 20 mm, following the length of the wood fibres found in the literature review.

The rice husk collected from the rice mill was partially ground. The study by Sasui et al. [47] showed that 2 % rice was the optimal amount for unground and fine ground rice husk, yet 4 % gave the highest increase in compressive strength for medium ground rice husk. Following the first 2 two mixtures, it was chosen to double the percentage of the rice husk for the second mixture as well.

In all mixtures water was added to reach the optimal moisture content (OMC) following the drop test as described in the literature review. The amount of water depended on the additive, where rice husk mixture needed a lot more water than pine needle mixture to get the desired consistency, crumbling and scattering resulting from the drop test.

The different material compositions that were tested were as shown in Table 2.

Table 2: Test sample composition

Sample:	**Fibrous additives:**	**Percentage:**
Reference	None	n/a
Mixture 1	Straw	1 %
Mixture 2	Straw	2 %
Mixture 3	Pine Needle	1 %
Mixture 4	Pine Needle	2 %
Mixture 5	Rice husk	4 %
Mixture 6	Rice husk	8 %

4.2 Making the samples

To make the samples different moulds were used. For the thermal conductivity tests a small wooden formwork and tamper was made. The compressive and tensile strength samples used a metal concrete testing mould and wooden tamper. In Table 3 the tested properties are shown, including the testing instruments. In the following sections a more detailed description of each test method is given.

Table 3:Laboratory equipment and sample size

Tests:	Sample size:	Testing Instruments:
Thermal Conductivity At 33 %, 60 % and 95 % RH	50 mm × 50 mm × 50 mm	Thermal Constants Analyser, climate controlled box and a scale
Compression Strength	150 mm × 150 mm × 150 mm	Universal Testing Machine
Tensile Strength	Diameter = 100 mm Height = 200 mm	Universal Testing Machine
E-modulus	Same sample	Universal Testing Machine

4.2.1 Thermal Conductivity

For determining the thermal conductivity of the soil mix with additives, the thermal constants analyser, Hot Disk TDS 2 500, was used. Each sample was made with the earth mixture, a tamper that consisted of 4 layers. The 50 mm × 50 mm × 50 mm cube consisted of 4 layers of earth and was tamped with a small sledge hammer and with 5 strikes per layer.

The measurements were conducted at 3 different conditions 33 % RH, 60 % RH and 95 % RH, approaching values for different seasons. Each measurement was done 3 times on 3 different faces of the cubes. The three conditions were maintained in a climate chamber and with 2 boxes with saturated salts solutions to create the desired relative humidity in a closed environment. With magnesium chloride at 20 °C a relative humidity of 33 % was achieved and with potassium nitrate a relative humidity of 95 % [48]. The climate chamber at Lund University has a constant temperature of 20 °C (needed for the saturated salt solutions) and a relative humidity of 60 %.

The samples were measured on a scale (Mettler Toledo PG603-S) with an accuracy of 1 milligram. After reaching moisture equilibrium, meaning no fluctuations in weight, the samples were placed in a plastic container to prevent the properties from changing while the measurements with the Thermal Constants Analyser TDS 2 500 S were conducted. The following parameters were used:

- Hot disk probe : Type 5 501
- Measurement time : 80 seconds
- Power output : 184 mW
- Scanning rate : 3 scans per 15 minutes

4.2.2 Mechanical Tests

The rammed earth specimen were made in the laboratory at the College for Science and Technology. Each sample was made with the earth mixture, a tamper that consisted of 4 layers, this was both the case for the cube and cylindrical moulds. It was not possible to load the moulds in one flight corresponding to the thickness of the actual building method.

In the 150 millimetre cube each layer was compacted with a (50 mm by 50 mm) tamper and 45 hits with a small sledge hammer, this resulted in the earth becoming slightly shinny. In between the different layers' water was sprinkled on the tamped surface to 'activate' the clay and ensure proper binding in-between the layers as stated in the Indian Standard[15].

In the cylindrical mould each layer was compacted with a tamper (Ø100 mm) and 10 hits with a small sledge hammer or until the earth became shinny. In between the different layers' water was sprinkled on the tamped surface to 'activate' the clay and ensure proper binding in-between the layers. Both the samples had the same feeling to the touch when pressing it when following this method.

The method used for testing the compressive and tensile strength will be made public in a paper after the UTM in Bhutan is operational and the test have been conducted.

4.3 Thermal Conductivity of an *in-situ* Rammed Earth Wall

To quantify the impact on energy use and thermal comfort on a traditional dwelling a reference building was used. The areas of the reference building were measured to create a 3D model in Rhinoceros 3D. The thermal conductivity of the façade construction was measured following the protocol in standard NEN ISO 9 869-1 [12]. This was done with the following tools:

- Omega HFS-4 heat flux sensor with built in K-type thermocouple connected to an Omega RDXL4SD data logger on the internal surface
- Omega T-type thermocouple connected to an Omega RDXL4SD data logger on the internal surface, both had a 60 second measurement interval.

On both the thermocouple and the heat flux sensor, heatsink paste was used for better contact with the construction. The thermocouple and heat flux sensor was attached to the wall using copper tape.

The recommended minimum 3-day measurement time was not reached, due to a time constraint only a 2-day measurement was possible. The data used for calculating the thermal conductivity was the data during night-time where the temperatures fluctuations are small.

Furthermore, the data logger used was not designed for a heat flux's sensor. It was designed for a thermocouple. This resulted in an output in degrees Celsius, this needed to be converted back to voltage (using the K-type calibration equation), and then converted into heat flux. Using a multi-meter, the 'zero' was determined and the measured values were corrected. The difference in the output of the data logger was on average 40 % higher than the measured values of the multi-meter. There were 10 measurements conducted with the multi-meter at different temperatures to determine the measurement error.

4.4 Energy and Thermal Comfort Simulation

The engine used for the dynamic energy simulations was EnergyPlus [8]. Rhinoceros 6 a 3D modelling environment was used to visualize a model [50]. The parameters were assigned through the visual scripting plug in Grasshopper and Ladybug Tools[51][52].

The Energy Plus weather file for Thimphu was used, this file was provided by the University of Bhutan. The indoor thermal comfort was determined by visualising, the change in, the operative temperature.

The in Bhutan measured reference building was used to compare the earth mixtures. The thermal conductivity of the earth mixture at 60 % RH was used. Both free running (unconditioned) and conditioned situations were tested. Besides only improving the thermal conductivity of the rammed earth wall the effect of altering other parameters was also tested, including the infiltration. When speaking of an infiltration rate in air changes per hour (ACH), this is at 50 pascals underpressure. The 6 different cases simulated for each material were:

1. Free running building with an infiltration rate of 75 ACH;
2. Free running building with an infiltration rate of 10 ACH;
3. Free running building with a 4 kW kitchen stove and an infiltration rate of 10 ACH;
4. Fully heated top floor, and an infiltration rate of 10 ACH;
5. Fully heated top floor, an infiltration rate of 5 ACH, improved insulation values for the floor, roof, and *rabsel* and double glazing.

Internal gains by people, electrical equipment, and lighting were not taken into account, as it was not part of the scope of this research to investigate the behavioural patterns and internal gains in Bhutanese residential buildings. Nor was there any additional ventilation added for the inhabitants of the building, as the infiltration rate was assumed to be sufficient. The improved infiltration rate was also assumed to be sufficient to prevent moisture accumulation in the building and prevent mould growth as described in 3.3.1.

A detailed description of the building and the parameters used for the different simulations are shown in chapter 5.

4.5 Survey Building Properties and Thermal Comfort

A questionnaire was sent out to the 1 000 students of The Royal University of Bhutan – College of Science and Technology. This questionnaire focussed on the type of buildings they lived in and the perception of thermal comfort in traditional Bhutanese residential dwellings. The results were used to compare the results from the simulations. The questions can be found in Appendix 1.

5 Properties of the Reference Building

5.1 Visualisation of the Building

The building used as a reference model is located in the Paro Valley, at an altitude of roughly 2 000 metres. It is a three story typical residential building. The bottom 2 floors, including internal walls, comprise of a rammed earth structure. The top floor is half rammed earth and half *rabsel* (wooden construction) with *shamig* panels. The building is 13 metres by 9.5 metres and roughly 13 metres high. Above the top ceiling there is a flying hip gable roof. The roofs lowest point is elevated 1.7 metres from the flat roof construction. The highest point is approximately 3 metres above the flat roof construction. The overhang of the roof is 2 metres.

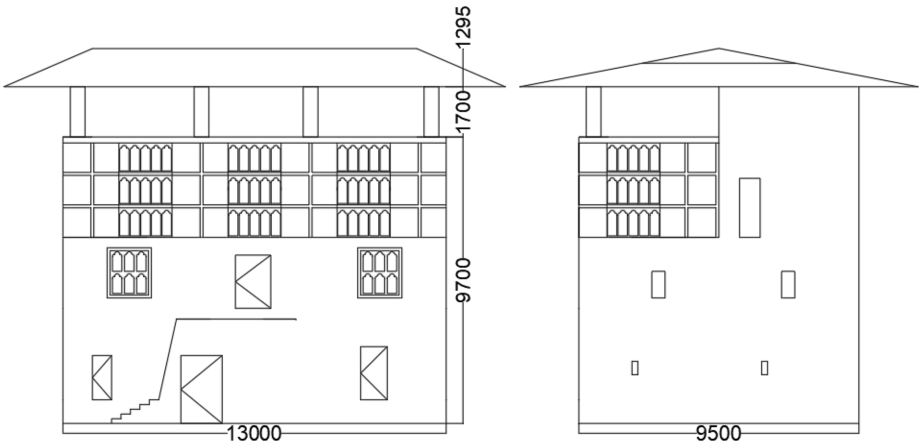

Figure 16: South west and south east façade, measurements in millimetres

Only the top floor will be analysed, the lower levels don’t have living quarters. The bottom floors however, were included in the simulation to take the unconditioned zones thermal capacity into account.

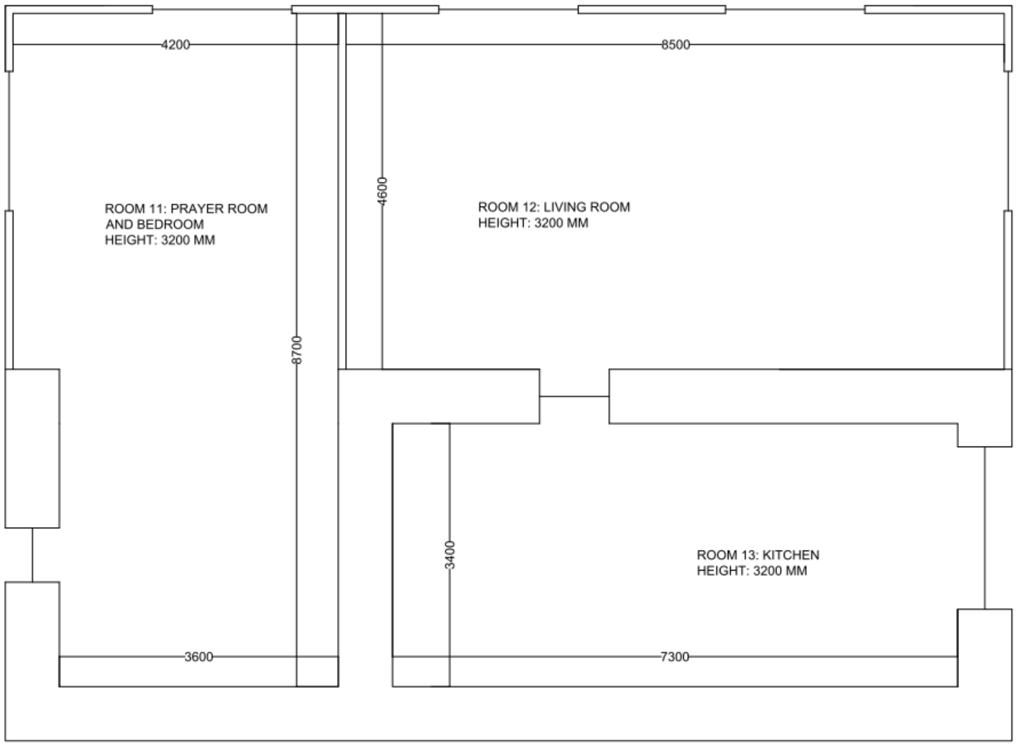

Figure 17: Floor plan top floor, bedroom, living room and kitchen, dimensions in millimetres

5.2 Base Case Building Materials

In the following section the different materials used are described. The flat roof consists of a layer of earth on top of straw. The bamboo is perpendicular to the crossbeams have large gaps in between them and therefore assumed not to add to the insulation value. The interior and exterior walls are rammed earth. The façade construction or *rabsel* is a 25 mm wood board, covered with earth. The doors and floors are made with 25 mm wood boards, this is also the case for the interior wall in between the bedroom and living room. The material properties of the building are stated in Table 4 according to SS-EN ISO 10 456: 2007 [53], unless stated otherwise.

Table 4: Material properties of the reference building

Construction Properties:	Thickness / m	Bulk Density / kg / m³	Thermal Conductivity / W / (m × K)	Specific Heat / J / (kg × K)
Roof:				
Earth	0.15	1 800	1.5	700[1]
Straw [54]	0.02	400	0.045	2 000
In/ext. wall	0.7	1 840	0.76[1]	700[1]
Rabsel:				
Earth	0.05	1 800	1.5	700[1]
Wood	0.025	700	0.18	1 600
Door	0.025	700	0.18	1 600
Floor/ceiling	0.025	700	0.18	1 600

[1]As per result of thermal constants analyser

The windows consist of single pane glazing with a wooden frame and a assumed combined U-value of 5.4 W / (m² × K) according to Table 2.4-10, and the solar heat gain factor (SHGF) is 0.82 as per Table 2.5-1 from the *Handboek Installatietechniek* [55].

5.3 Building Properties of Test Cases

The following table gives a summary of the different inputs used in the different simulations. The text 'all' under wall indicates that the reference material and the 6 mixtures with additives were simulated.

Table 5: Building Performance Simulations inputs (U-value roof, window, floor and rabsel in W / (m² × K))

	Heated	Stove	ACH	Wall	Roof	Window	Floor	*Rabsel*
Case 1	No	No	75	All	1.88	5.4	7.2	5.6
Case 2	No	No	10	All	1.88	5.4	7.2	5.6
Case 3	No	Yes	10	All	1.88	5.4	7.2	5.6
Case 4	18 °C	No	10	All	1.88	5.4	7.2	5.6
Case 5	18 °C	No	5	All	1.00	3.2	1.0	1.0

The measured thermal transmittance of the rammed earth specimen resulted in the thermal conductivity as stated in Table 6.

Table 6: Resulting U-values in W / (m² × K) for rammed earth wall

Reference	1 % Straw	2 % Straw	1 % Pine	2 % Pine	4 % Rice Husk	8 % Rice Husk
1.08	0.88	0.73	0.93	0.93	0.86	0.7

The operational hours of the stove are according to a yet to be published study on thermal comfort and indoor air quality of Nepalese traditional buildings. Figure 18 shows these operational hours in summer and winter in Chame located at 2 600 metres. The stove has a 4 kW heating capacity [56]. In the simulation only the winter time operational hours were taken into account. There was no differentiation between summer and winter.

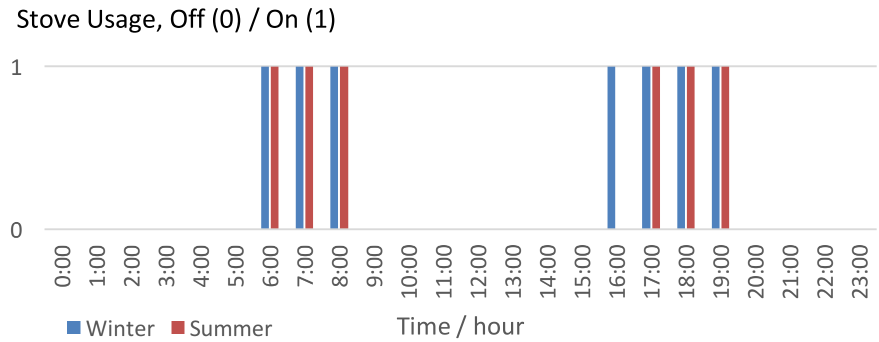

Figure 18: Operational hours of a wood fired kitchen stove

The improved infiltration rate of 10 ACH according to Jentsch et al. [37] who stated: 'This [A 10 ACH infiltration rate] could probably be achieved with comparably simple improvements to construction methods and build quality'. According to a field study on timber frame buildings by Kalamees [57], 5 ACH at 50 Pascal was common in wood frame buildings built between 1970 and 2005 in different European countries, this was used as a value for case 5. The *rabsel* timber frame construction is assumed to meet this air tightness.

The improved insulation values in case 5 was based on an arbitrary decision, where the amount of straw was increased in the energy model until a U-value of 1 W / (m² × K) was achieved. In case of the *rabsel* an extra wooden board was added to keep the straw 'in place'. The double glazing including wooden frame has a SHGF of 0.7 as per Table 2.5-1 [55].

6 Results

This chapter will show the results for the conducted tests and simulations. It will start with the results of the Thermal Constants Analyser, and the *in-situ* measurement of a rammed earth building. Thereafter, the results of the different Energy Performance Simulations and the final section shows the results of the conducted survey.

6.1 Results Thermal Conductivity tests

Table 7 shows the results from Thermal Constants Analyser conducted in the laboratory at Lund University. The results are an average of the three tests.

Table 7: Results laboratory tests thermal conductivity

Material Composition	**Thermal Resistance / W / (m × K)**			**Wet Bulk Density[1] / kg / m³**
Condition:	33 % RH	60 % RH	95 % RH	
Reference:	0.72	0.76	0.85	1 840
1 % Straw	0.68	0.62	0.69	1 839
2 % Straw	0.54	0.51	0.60	1 652
1 % Pine	0.59	0.65	0.84	1 878
2 % Pine	0.61	0.65	0.76	1 835
4 % Rice Husk	0.59	0.60	0.67	1 793
8 % Rice Husk	0.42	0.49	0.52	1 672

[1]Measured in Bhutan at atmospheric conditions after 21 days drying time (average of 3 mechanical and 3 tensile strength samples)

6.2 Field Study

An in situ measurement was conducted during a 2-day period, with 2 thermocouples, a heat flux sensor and 2 data loggers. The measured thermal conductivity of the rammed earth construction after correction was 1.2 W / (m × K). It was not possible to determine the dry density.

6.3 Results Mechanical Tests

The universal testing machine was non-operational during the timespan of this thesis. However, the data will be made public in a paper after the tests have taken place.

6.4 Results Energy Simulation and Thermal Comfort

In the following sections the results of the 6 different energy simulations will be presented.

6.4.1 Results Bedroom Case 1, Case 2 and Case 3

The following two figures will show the operative temperature and the net gains and losses of the bedroom during a three-day period from the 12th of January till the 14th of January.

Figure 19 shows the operative temperature of the three unheated cases. It is visible that decreasing the number of air changes per hour from 75 to 10 ACH at 50 Pa increases both the minimum and the maximum temperature during the winter situation. Furthermore, the figure shows a slight increase in temperature of the bedroom, as a result of a woodstove in the kitchen in case 3.

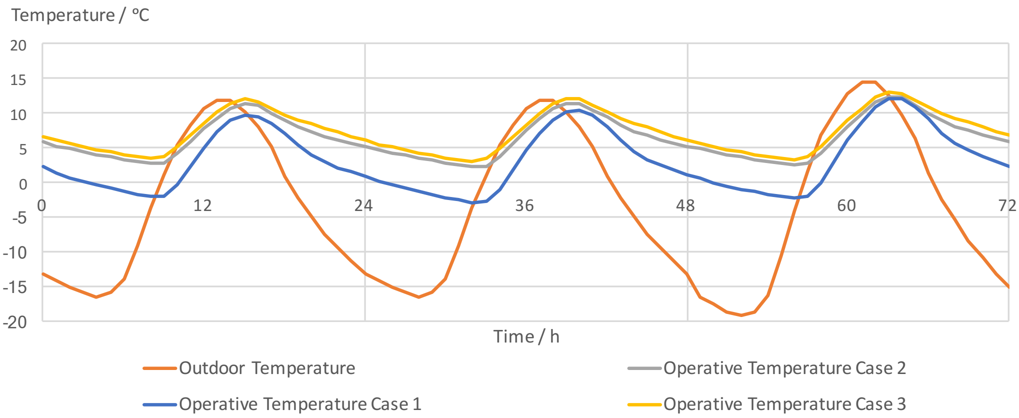

Figure 19: Three-day outdoor and operative temperature profile, bedroom three unheated cases

Figure 20 shows the net gains and losses of the building, with the gains being positive and the losses being negative. It is visible that with decreasing the infiltration rate, the infiltration losses decrease, however the transmission losses increase. With a wood stove, the energy losses increase and the energy gains decrease.

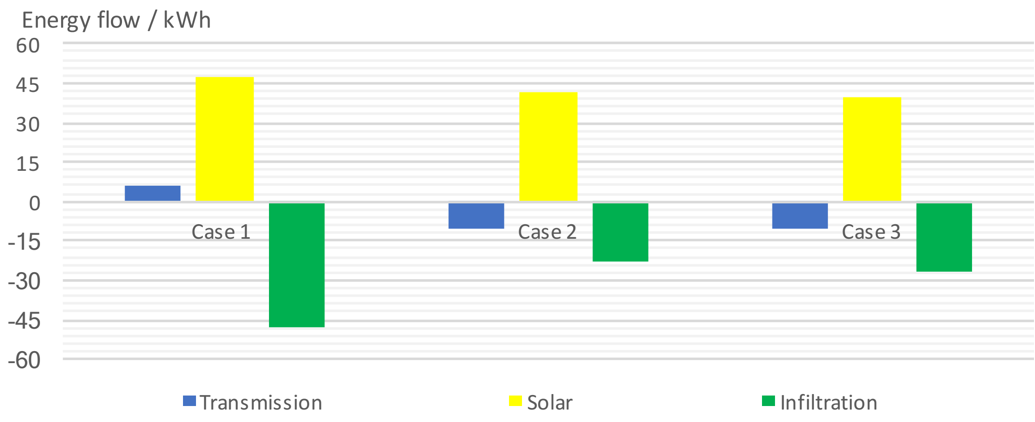

Figure 20: Net energy gains and losses, bedroom

6.4.2 Results Kitchen Case 1, Case 2 and Case 3

The following two figures will show the operative temperature and the net gains and losses of the kitchen during a three-day period from the 12th of January till the 14th of January.

Figure 21: Three-day outdoor and operative temperature profile, kitchen three unheated cases shows the operative temperature of the three unheated cases, with case 3 having a wood stove for cooking. Again, it is visible that decreasing the number of air changes per hour from 75 to 10 ACH at 50 Pa increases both the minimum temperature. However, the maximum temperature decreases. Furthermore, the figure shows an increase in temperature of the kitchen, as a result of the use of a woodstove.

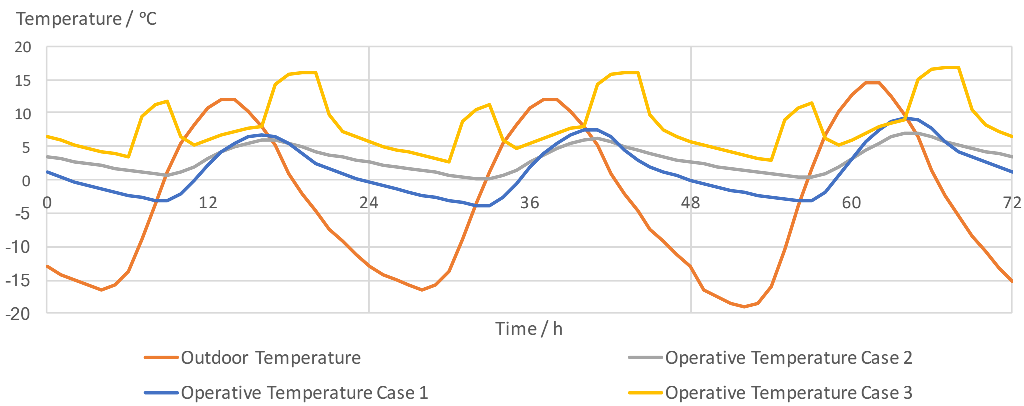

Figure 21: Three-day outdoor and operative temperature profile, kitchen three unheated cases

Figure 22 shows the net gains and losses of the kitchen, with the gains being positive and the losses being negative. It is visible that with decreasing the infiltration rate, the infiltration and transmission losses decrease. With a wood stove, the energy losses increase and the energy gains decrease.

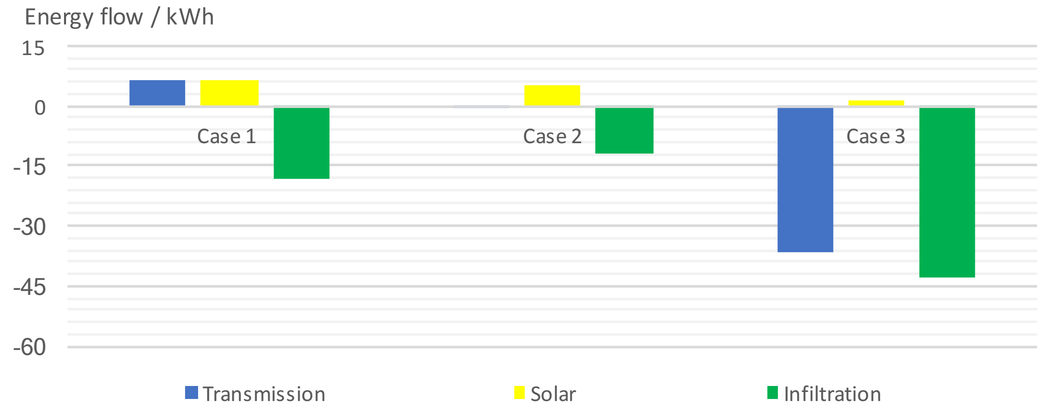

Figure 22: Net energy gains and losses, kitchen

Figure 22 shows the net gains and losses of the building, with the gains being positive and the losses being negative. It is visible that with decreasing the infiltration rate, the infiltration and transmission losses decrease. With a wood stove, the energy losses increase and the energy gains decrease.

6.4.3 Results Living Room Case 1, Case 2 and Case 3

The following two figures will show the operative temperature and the net gains and losses of the living room during a three-day period from the 12th of January till the 14th of January.

Figure 23 shows the operative temperature of the three unheated cases, with case 3 having a wood stove for cooking. Again, it is visible that decreasing the number of air changes per hour from 75 to 10 ACH at 50 Pa increases both the minimum and the maximum temperature during the winter situation. Furthermore, the figure shows an increase in temperature of the living room, as a result of the use of a woodstove in the kitchen.

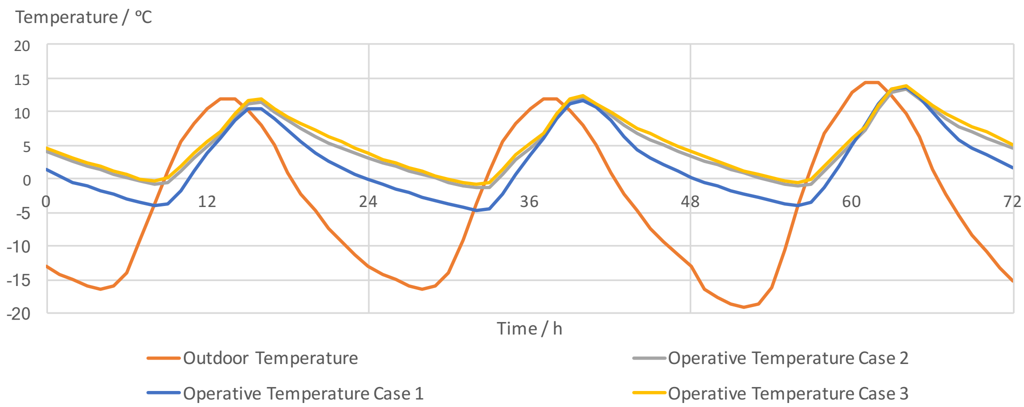

Figure 23:Three-day outdoor and operative temperature profile, living room three unheated cases

Figure 24 shows the net gains and losses of the living room with the gains being positive and the losses being negative. It is visible that with decreasing the infiltration rate, the infiltration losses decrease and transmission losses increase. With a wood stove, the energy losses increase and the energy gains decrease.

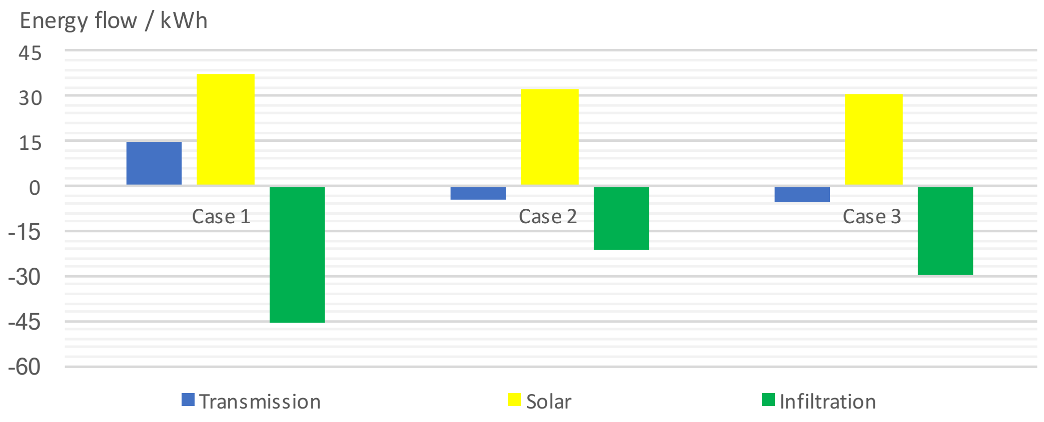

Figure 24: Net gains and losses, living room

6.4.4 Comparison Case 1, Case 2 and Case 3 with Additives

Besides the reference cases as shown before, the improved materials have also been simulated. The results show that the impact of additives on maximum and minimum operative temperature in the bedroom, kitchen and living room are insignificant. The results showed that in an unheated case the minimum indoor temperature decreases marginally with an increasing insulation value, the opposite is true for a maximum indoor temperature value, which increases marginally with an increasing insulation value. The maximum difference in temperature decrease and increase was respectively 0.4 °C and 1.2 °C.

By categorising the previous numbers according to a temperature bandwidth of 5 °C. A better grasp of thermal comfort can be achieved. Figure 25 shows that improving the air tightness and increasing the insulation values, improves the operational temperature, but only to a certain extent. In case of the stove usage the temperatures during warmer periods increase to uncomfortable levels.

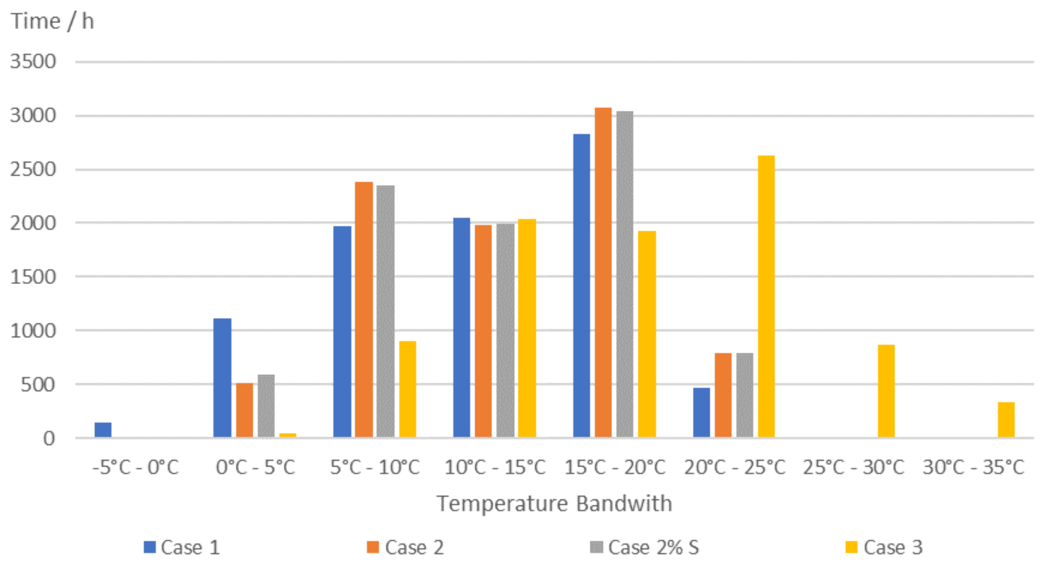

Figure 25: Number of hours within a 5 degree bandwidth for different cases

6.4.5 Results Case 4

Case 4 is equal to case 2 with the exception that the top floor is conditioned to 18 °C. The following table shows the energy use and the fire wood equivalent of a the fully heated top floor for different additives.

Table 8: Energy use of a fully heated top floor

	Energy Use / kWh / (m² × a)			Fire wood equivalent / kg / a		
Sample	Bedroom	Kitchen	Living	Bedroom	Kitchen	Living
Reference	196	239	267	1 235	1 754	2 270
Straw 1%	196	237	267	1 232	1 740	2 271
Straw 2%	195	235	267	1 225	1 727	2 272
Pine 1%	196	238	267	1 232	1 743	2 271
Pine 2%	196	238	267	1 233	1 743	2 271
RRH 4%	195	237	267	1 229	1 737	2 271
RRH 8%	194	235	267	1 220	1 723	2 271

Looking at the results it is visible that the improvement by adding insulation to the wall construction is only a couple kilowatt-hours per square meter per year. The following figure shows the gains, losses and improvement in thermal conductivity for the reference case and the case with 2 % straw. The results are shown per construction type and infiltration. The windows include the radiative energy. It is seen that improving the rammed earth construction decreases the heat loss through the wall by 41 % yet the transmission loss of the wall is only 5 % of the total energy loss, and therefor only has a limited impact on the total energy use as seen in Table 8.

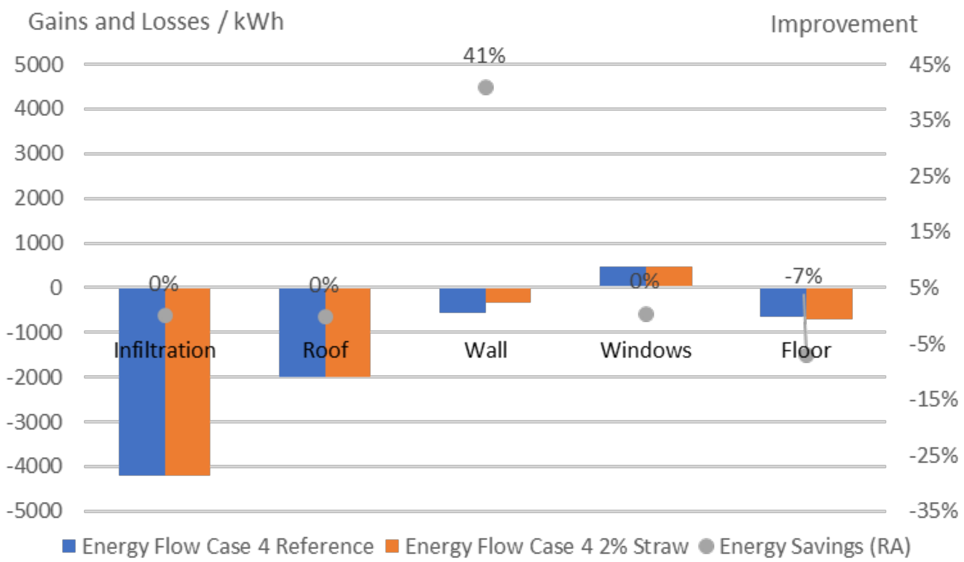

Figure 26: Energy flow kitchen Case 4 with gains being positive and losses negative

6.4.6 Results Case 5

The following table shows the energy use of a fully heated top floor for different additives. The air temperature set point was 18 °C.

Table 9: Energy use of a fully heated top floor with improved insulation

	Energy Use / kWh / (m² × a)			**Fire wood equivalent / kg / a**		
Sample	Bedroom	Kitchen	Living	Bedroom	Kitchen	Living
Reference	109	144	134	684	1 058	1 143
Straw 1%	107	141	134	675	1 038	1 141
Straw 2%	105	139	134	664	1 020	1 139
Pine 1%	107	142	134	677	1 042	1 142
Pine 2%	108	142	134	678	1 042	1 142
RRH 4%	107	141	134	672	1 034	1 141
RRH 8%	105	138	134	658	1 015	1 137

Looking at the results it is visible that compared to Case 4 the improvement is significant. The following figure shows the gains, losses and improvement in thermal conductivity for case 5 with the reference material and with 2 % straw. The results are shown per construction type and infiltration loss and gain. The windows include the radiative energy. It is seen that improving the rammed earth construction decreases the heat loss through the wall with 42 % yet transmission loss is only 8 % of the total energy loss, resulting in a 4 % total savings.

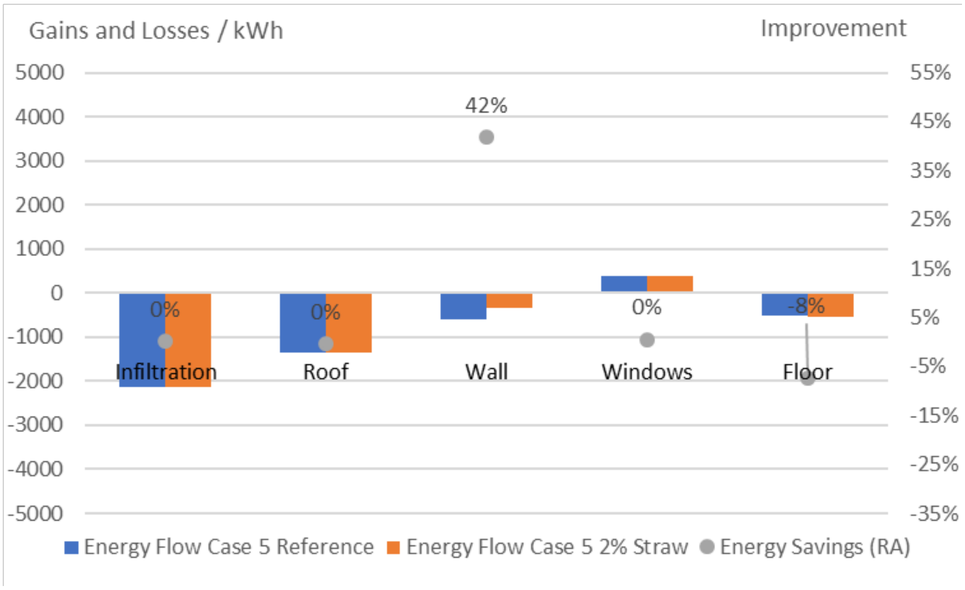

Figure 27: Energy flow kitchen Case 5 with gains being positive and losses negative

6.5 Thermal Behaviour of the Building

To gain a deeper understanding of the results of the building simulations, and the effect of thermal mass on the thermal comfort levels; the hourly values were further investigated. Of Case 2 with the properties of the reference material, two additional simulations have been made. One with rammed earth walls without mass and the second with no mass in any of the constructions.

The following three figures show the hourly results of the simulation on the 12th of January of the refence year. On the left axis (LA) the temperature is shown and on the right axis (RA) the gains and losses, with gains being positive and losses negative.

Figure 28 shows the reference case, in this figure it is visible that the transmission gains and losses are a significant amount of the total gains and losses. Furthermore it is visible that the operative temperature fluctuates roughly 5 degrees Celsius during day and night-time.

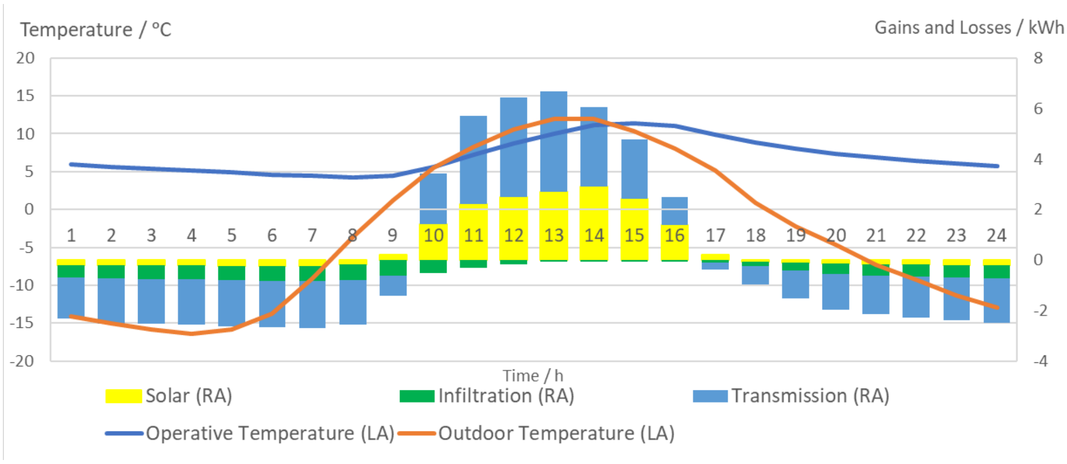

Figure 28: Hourly values Case 2 reference, regular mass

Figure 29 shows a large difference in transmission gains/losses in comparison to Figure 28. This is due to the fact that the energy absorbed and desorbed by the opaque constructions is treated as transmission gains and losses. Meaning that in the building performance simulation the transmission gains/losses also take into account energy stored in the construction. Furthermore, it is visible that by decreasing the mass of the construction the temperature increase occurs faster, the dampening effect of the thermal mass is clearly visible.

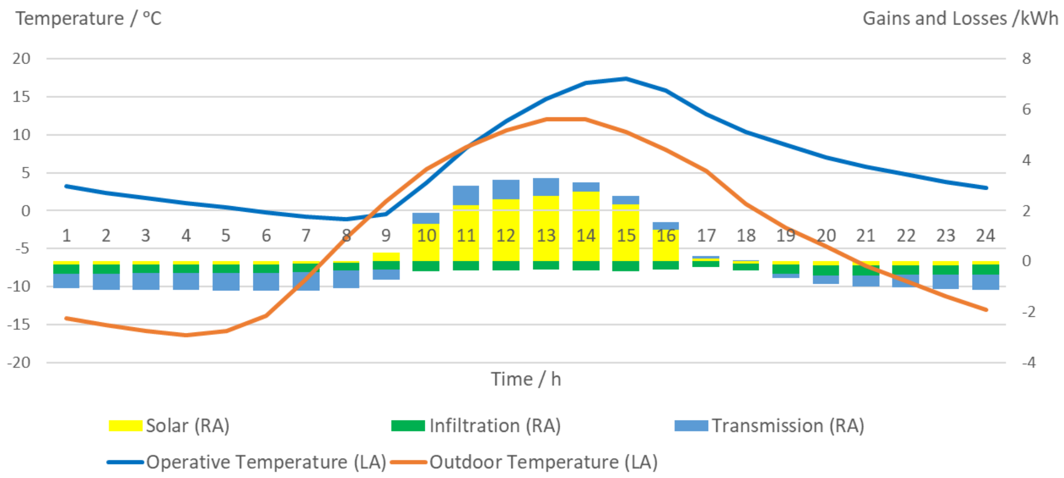

Figure 29: Hourly values Case 2 reference, no mass in rammed earth

Figure 30 shows that the temperature fluctuates more when removing all mass than in comparison to Figure 29. The energy storing/buffering capacity of the building is non-existent resulting in a transmission loss.

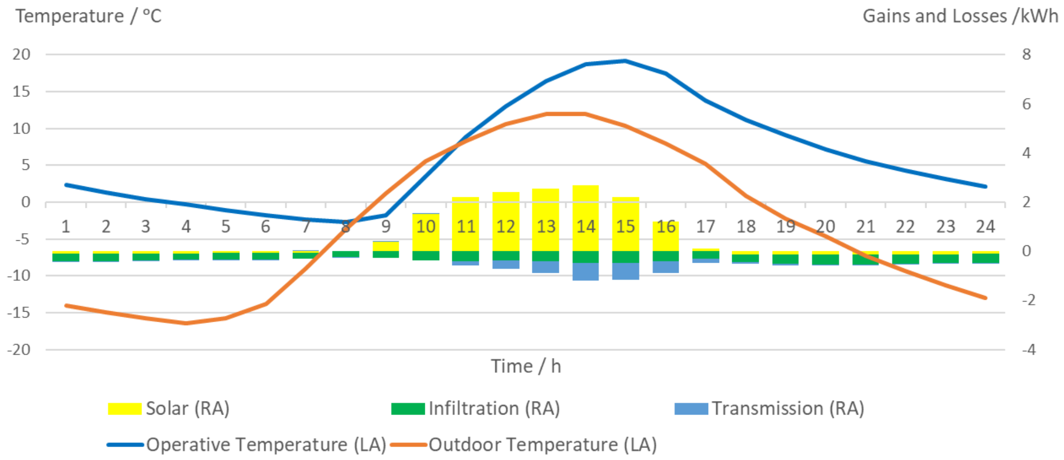

Figure 30:Hourly calues Case 2 reference, no mass in entire building

6.6 Results Thermal Comfort Survey

Among the students of the College of Science and Technology a survey was sent out. Of these 1 000 students 50 students responded and are merely an indication of what could be the status quo. The students come from all over Bhutan, and have been asked questions regarding thermal comfort in natural buildings. Thermal comfort in concrete and clay fired brick buildings was not part of the questionnaire. However, 7 answers were related to concrete and clay fired brick buildings. These results have not been taken into account. This sections shows the results of the questionnaire.

What type of natural building did/do you live in?

Figure 31 shows that 28 % of the students live in earth or clay buildings.

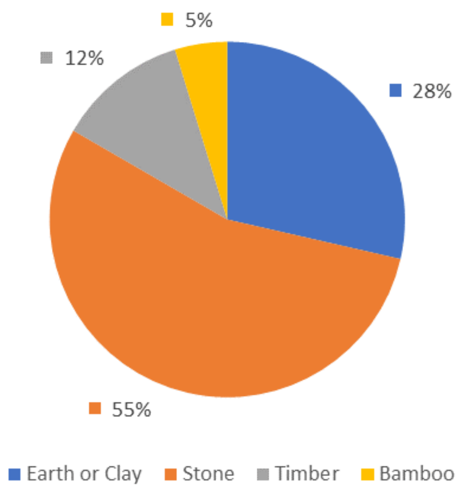

Figure 31: Types of buildings inhabited by respondents

What district is this building located in?

The majority of the respondents by descending order lived in Tashigang, Tashi Yangtse Thimphu, Paro, Bumthang, Tsirang, Mogar as seen in Figure 32. The brackets indicate the climate zones. A sub-tropical climate (1), a temperate climate (2) and an alpine climate (3).

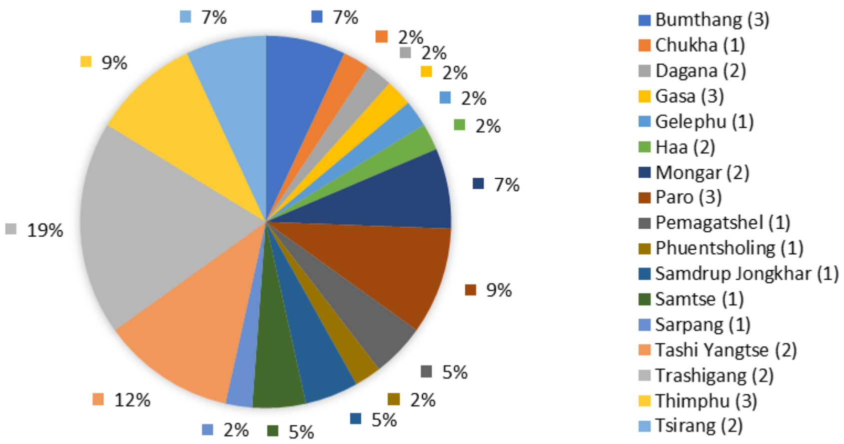

Figure 32: Location of building inhabited by respondents

If you answered 'Earth or Clay' were/are there any fibres used in the construction? If yes, what type of fibres?

There was only a limited number of respondents who had knowledge of fibres being used in the earth or clay buildings. How the fibres are used however was not disclaimed.

- Pine Needles : 3 responses
- Straw : 4 responses
- Bamboo : 2 responses

Was/is the building heated?

The number of houses unheated was larger than the heated houses as is shown by the following results

- Yes : 20 responses
- No: : 23 responses

What was/is the main source of heating?

The main source of heating among the respondents was a *bhukari* or wood stove. The two respondents that had electric heaters also stated passive solar heating.

- Fire Wood : 18 responses
- Electric Heater : 2 responses
- Passive Solar: : 2 responses combined with Electric Heater

Were/are all rooms heated?

- Yes : 1 response
- No : 19 responses

If no, what rooms were/are heated?

Not all respondents answered this question, yet the majority of the kitchens was heated over the living rooms.

- Kitchen : 8 responses
- Living Room : 4 responses

How would you describe the indoor thermal comfort during winter and summer time?

Figure 33 shows how the respondents perceived the indoor thermal comfort during summer and winter time, the scale is left of the figure. The boxplot shows that 50 % of the respondents are slightly cool, to slightly warm in winter time with the mean leaning towards slightly cool. The bottom quartile indicates 25 % are cool to cold and the top quartile indicates that the respondents feel slightly warm to warm during winter time.

In the summer case 50 % of the respondents feel neutral to warm with the top quartile feeling warm to hot. The bottom quartile is feeling neutral to cool.

Scale:

+ 3 Hot

+ 2 Warm

+ 1 Slightly warm

0 Neutral

- 1 Slightly cool

- 2 Cool

- 3 Cold

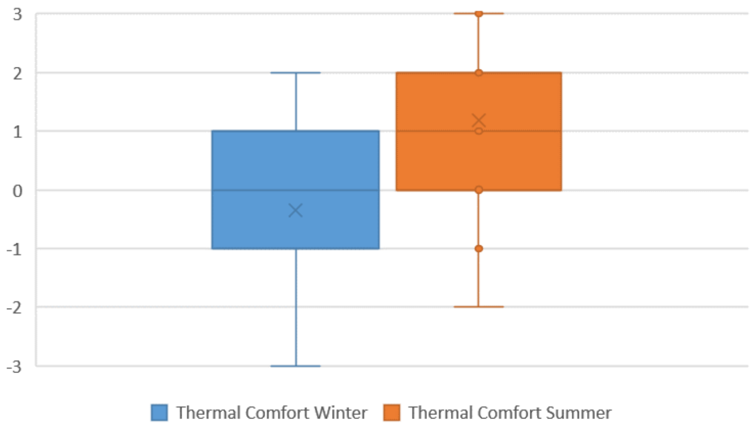

Figure 33: Thermal Comfort Levels in Winter and Summer

What would you say a typical indoor temperature range is/was in winter and summer time?

Figure 34 shows the room temperature the respondents believed the room to be during summer and winter time. It was not specified whether this temperature is based on feeling or actual measured values. It shows that the 50% of the answered values are between 8 °C and 15 °C during winter time and during summer time 21 °C to 27 °C.

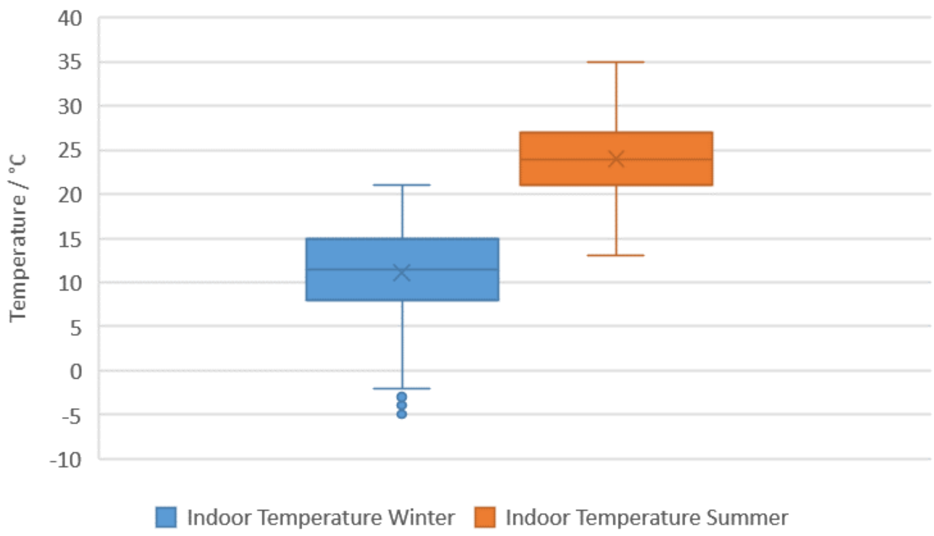

Figure 34: Indoor Temperature Range During Winter and Summer

The previous two figures showed the results for the whole of Bhutan. To compare the data to the energy model, the answers for the in Thimphu and Paro located houses give a more accurate result. There were 8 respondents who live/lived in the Paro/Thimphu region.

Figure 35 shows the results of the questionnaire where the students have answered what the temperature range is during summer and winter time. The results show that during wintertime 50 % of the numbers within the rage are between 6 ºC and 11 ºC the top quartile shows that the temperature reaches 15 ºC and the bottom quartile shows that the temperature reaches 3 ºC. In the summer case 50 % of the responses indicates that the temperature is between 20 ºC and 26 ºC, with the top quartile showing temperatures up to 30 ºC and the bottom quartile temperatures reaching as low as 15 ºC.

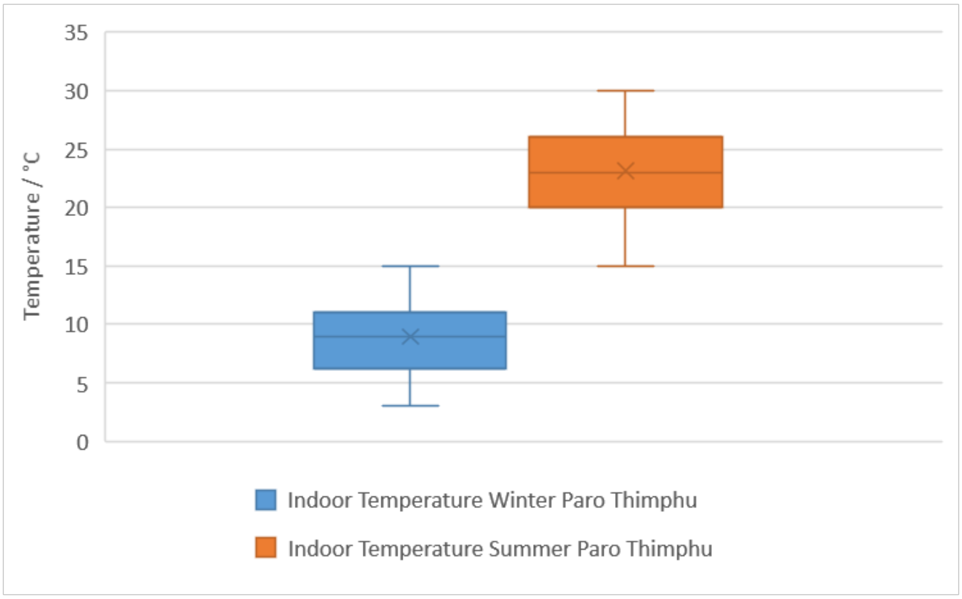

Figure 35: Indoor Temperature Range During Winter and Summer in Paro and Thimphu

Besides the students being asked about their perception of the indoor temperature, they were also asked to indicate how they felt indoor. The following table shows that people are generally cold with the average being slightly cool. In summer time the people are slightly warm to hot with one outlier who indicated to be slightly cool. The results are shown in Figure 36.

Scale:

+ 3 Hot

+ 2 Warm

+ 1 Slightly warm

0 Neutral

- 1 Slightly cool

- 2 Cool

- 3 Cold

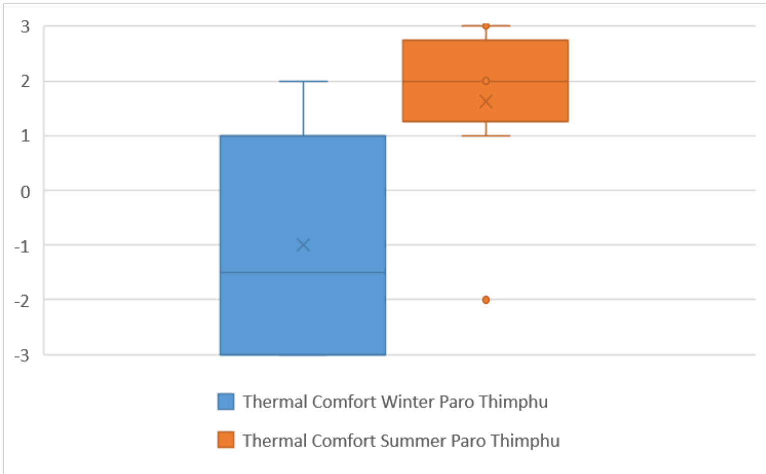

Figure 36: Thermal Comfort Levels in Winter and Summer in Paro and Thimphu

7 Discussion

This thesis looked at improving the thermal conductivity of rammed earth constructions by adding locally available natural additives.

7.1 Rammed Earth Constructions

First the method for rammed earth constructions was investigated. The method in Bhutan uses wooden tampers to work the loam in between a closed formwork, until it reaches its desired density. The literature review stated that the dry density of rammed earth typically varied between 1 700 kg/m³ and 2 200 kg/m³. Where the *in-situ* measurements as shown in the section ‘ Properties of Earth’ measured the wet density that ranged roughly from 1 700 kg/m³ to 2 000 kg/m³. The difference between the apparent or bulk density and the dry density is that the dry density only takes into account the weight of the solids and not the water/moisture in the sample, as the wet bulk density does. Therefore, the *in-situ* measurements cannot be compared one on one to the literature, and the discrepancy between the two results needs to be kept in mind. The difference in mechanical strength between the literature and the *in-situ* measurements also indicates that the Bhutanese rammed earth constructions might have a slightly lower density. However, this may also be due to the material composition, which a particle size distribution test would show.

7.2 The use of Additives

To improve the thermal properties of the rammed earth constructions natural ‘lightweight’ additives were added to reduce the density of the admixture and, with it, improve the thermal conductivity. The amount of studies found on the use of additives in rammed earth constructions was limited. Only a few studies, or recommendations where found related to the use of additives in rammed earth constructions. It was not possible to make a conclusion on what would be the best natural aggregates to test based on the literature review, as the availability of aggregates was uncertain, this could only be determined after arrival in Bhutan and was dependant on the local contacts in Bhutan. After receiving the materials, the corresponding literature was used to determine the percentage of additive. The percentage of additive by weight for rammed earth construction was small, up to 1 %. Other earth construction methods, such as cob and adobe bricks have far larger amounts of aggregates to reduce the density of the loam mixture to levels below 1 200 kg/m³, as seen in the literature review. These wet methods, cob and mudbricks, allow for a better contact between the natural aggregates and the clay particles and therefore adhere/bind better.

7.3 Making of Samples

During the mixing of the fibres it was difficult to mix large amount of fibres even though the literature showed it to be possible in different earth building techniques. It was not possible to follow the literature and the total amount of fibre used was based on empirical evidence. The length of the aggregates was based on the maximum length of the wood aggregates as stated in the literature review. The straw mixture with 2 % straw, had to many ‘knots’ and was not able to adhere, therefore the fibres where cut even though the literature showed that this had negative impact on the tensile strength. After cutting the fibres, the amount of fibres was not increased.

The use of rice husk at both 4 % and 8 % by weight in both cases resulted in fungal growth during the drying period. The husk was obtained from a rice mill where the husk was grinded off the rice grain. The grinding of the rice husk presumably ground off some of the rice kernel and this together with the moist soil sample resulted in a perfect growth condition for the fungi. The fungal growth also occurred in the climate chamber in Sweden when the sample was conditioned to 95 % relative humidity, no growth was visible at 60 % relative humidity.

7.4 Thermal Conductivity of the Samples

The samples that were made in Bhutan and tested on the Thermal Constants Analyser at 60 % relative humidity in Sweden had thermal conductivity (lambda) values of 0.76 W / (m × K) to 0.49 W / (m × K) from respectively the reference sample to the best performing sample with 8 % raw rice husk. The wet bulk densities ranging from 1 840 kg/m³ to 1 652 kg/m³ where with the use of pine needles the bulk density increased (1 878 kg/m³). Compared to the literature review, the lambda value at the same dry density was respectively 0.95 W / (m × K) and 0.75 W / (m × K). The discrepancy between the values could be due to a combination of measurement conditions and the use of wet or dry density however, that was not stated clearly in the literature. Furthermore, the homogeneity of the samples could cause a discrepancy in the calculations.

7.5 Thermal Conductivity of *in-situ* Measurement

The thermal conductivity measurement during the field study resulted in a lambda value of 1.2 W / (m × K). The accuracy of this number however, is questionable. First of all, the equipment used for the measurement was not suitable for logging the desired data. Secondly, the conversion of temperature to millivolts and then to heat flux corrected with an average correction factor has large margin for error. The result seems plausible, but needs verification with the proper tools and the proper measurement time. The current measurement was only taken during a two-day period, where the standard advises a longer time advisable, especially for heavy constructions. The relation to the density of the material is also not available as there was no possibility to take a sample from the building.

7.6 Thermal comfort and Energy Use

Looking at the results of the energy simulations, it is clear that infiltration has a large impact on the high and low temperatures. During the cold hours of the year heat is extracted out the building, and during the warm hours of the year the heat is added to the building. By reducing the infiltration, the temperature increases during winter time and decreases during summer time.

A closer look at the transmission losses in the kitchen shows that the transmission gains during day time and losses during night time are similar in magnitude, even though the temperature difference between indoor and outdoor is far greater during night time (delta T 10 ºC vs. 20 ºC). A more logical result would be a higher transmission loss during the night (in kW) than transmission gain during the day (in kW). This was explained by decreasing the thermal storage of the 700 mm thick external rammed earth wall.

Looking at the results from the free running building. The lack of internal gains, was based on the behavioural patterns and internal gains of Bhutanese families and dwellings not being the part of the scope of this research. However, omitting these gains results in a non-realistic outcome. Nevertheless, the simulation with the stove in the kitchen can be used to educe the effect of the building with internal gains of residents.

In the case of the additives, the thermal conductivity has only improved the insulation value of the wall by roughly 35 % however, the amount of energy leaving the building through the façade is roughly 10 % resulting in a marginal saving of 3 % to 4 %.

Improving other parts of the buildings results in an increasing impact of the savings of the façade, however not significantly.

The questionnaire filled in by the students, showed a broad temperature range for the indoor temperature, and the how they experienced the thermal comfort indoors. The students who lived in houses in the Paro/Thimphu region had no heating. A closer look at the results showed that indeed the temperatures by the students were experienced as ranging from 3 ºC to 15 ºC during winter time and 15 ºC to 30 ºC during summer time. The accuracy of these results however, is questionable, these results are based either on the feeling of the students or based on actual measurements conducted by students at home. This was unspecified in the questionnaire. The results however do fall in the same temperature range as the simulations. The majority of the respondents indeed felt cold, yet not all of them. In a western building all occupants of the building would be highly uncomfortable. In this case there are still respondents who state to be comfortable at these temperatures. Indicating that the thermal comfort levels in the west are not equal to the thermal comfort levels in Bhutan.

8 Conclusion

This thesis aimed to improve the thermal conductivity of rammed earth constructions and with it the thermal comfort in Bhutanese rammed earth dwellings, located in the cold Thimphu region. This was done by firstly investigating the rammed earth construction technique and the different earth building techniques used in Bhutan. To improve the thermal properties of rammed earth buildings natural additives comprising of plant fibres and other aggregates were investigated. The locally available additives were then collected and used to make different test samples to measure different properties. The focus was on thermal properties but the effect on mechanical properties comprising of: compression, tensile strength and the elasticity were also investigated. A reference building in the Paro valley was measured and used to make a computational model. The results from the thermal constants analyser were used to simulate the improvement in operative temperature and energy use. This was done for different heated and unheated scenarios. The results of these simulations were then compared to the results of a questionnaire based on thermal comfort.

The fibres available were straw, pine needles and rice husk, these fibres were added by weight in the following percentages 1 % and 2 % for both straw and pine needles and 4 % and 8 % for medium ground rice husk. The biggest improvement in thermal conductivity was reached with 8 % rice husk, where an improvement of 35% was achieved, from 0.76 W / (m × K) to 0.49 W / (m × K). The straw mix with 2 % performed second best with a thermal conductivity of 0.51 W / (m × K). However, the fungi on the raw rice husk samples needs to be further investigated, to assure no potential health risk including the conditions at which the growth occurs. Therefore, the best performing material thus far is the 2% straw admixture.

By means of a building performance simulation the effect on the operative temperature and energy use of the improved buildings was simulated. The operative temperature of the three rooms in the free running building (unconditioned building) improved significantly when improving the air tightness of the building. Improving the thermal conductivity of the wall had minimal impact on the operative temperature.

With a heat source (a stove) in the free running building, an improving thermal conductivity he transmission losses reduced with improving thermal conductivity and thus improved the minimum operative temperature.

The building performed the same in the conditioned case where an improved thermal conductivity resulted in a reduced amount of energy loss. However, only improving the rammed earth construction in the wall had little impact on the total energy use. Where the façade only accounts for roughly 5 % of the total energy loss.

When improving the thermal conductivity of all opaque constructions to a U-value of 1 W / (m^2 × K), transparent constructions to a U-value of 3.2 W / (m^2 × K) and infiltration to 5 ACH at 50 pascals, the energy use was reduced significantly. When improving the other constructions, the impact of the improvement on the façade became more significant. The transmission losses through the facade accounted for 8 % of the total energy loss, yet only 3 % reduction was achieved with 2 % straw admixture.

In conclusion, the addition of fibres to a rammed earth wall construction alone does not result in an increase in thermal comfort, the savings in energy use of the wall construction is insignificant. Therefore, the other sources of energy loss in the building (e.g. infiltration and the overall building envelope) need to be addressed. Improving the thermal conductivity with 25 % to 30 % whilst potentially compromising the structural integrity of the load baring walls is not enough to approach 'western' levels of thermal comfort.

9 Summary

The thesis aimed to improve the insulation value of rammed earth constructions and, with it, improve the thermal comfort in Bhutanese rammed earth dwellings. The study focussed on rammed earth constructions in the cold climate in the Paro and Thimphu region.

To improve insulation properties of the rammed earth constructions, lightweight natural additives were added to soil suitable for rammed earth constructions. The benefit of natural additives, such as plant fibres, or plant aggregates is that this natural material has limited impact on the climate and it is readily available. The fibres that were abundantly available in the Paro and Thimphu region were: straw from a farm, pine needles from the trees and ground rice husk from a local rice mill.

The locally available fibres were used to make different test samples to measure different properties. The focus of this thesis was on thermal properties but the effect on mechanical properties comprising of: compression, tensile strength and the elasticity was also investigated. A reference building in the Paro valley was measured and used to make a computational model. The results from the thermal constants analyser were used to simulate the improvement in operative temperature and energy use. This was done for different heated and unheated scenarios. The results of these simulations were then compared to the results of a questionnaire based on thermal comfort.

By adding fibres to the earth mixture, the density of the material decreased and, with it, the thermal conductivity. The reference material improved from 0.76 W / (m × K) to 0.49 W / (m × K) with the 8 % raw rice husk mixture. Using these results to quantify the energy use and thermal comfort, showed that the addition of fibres to a rammed earth wall construction alone does not result in a significant increase in thermal comfort. The energy loss through the wall construction in a heated case is only 5 % of the total energy loss of the building. Therefore, improving the thermal conductivity with 25 % to 30 % results in an insignificant energy saving. When new buildings are constructed in Bhutan the following issues should be considered in order to build good buildings for the future:

1. Reduce Infiltration
2. Improve windows and doors
3. Improve building materials

However, in order to reach Western levels of indoor comfort, the rammed earth buildings need to be complemented with a proper insulation layer.

10 Appendix 1: Questionnaire on Thermal Comfort

Questions:

1. What type of natural building did/do you live in?
    a. Earth or Clay
    b. Stone
    c. Timber
    d. Bamboo
    e. Other: ….
2. What district is this building located in?
    a. …
3. If you answered 'Earth or Clay' were/are there any fibres used in the construction? If yes, what type of fibres?
4. Was/is the building heated?
5. What was/is the main source of heating?
6. Were/are all rooms heated?
7. If no, what rooms were/are heated?
8. How would you describe the indoor thermal comfort during winter time?
    a. Hot
    b. Warm
    c. Slightly warm
    d. Neutral
    e. Slightly cool
    f. Cool
    g. Cold
9. How would you describe the indoor thermal comfort during summer time?
    a. Hot
    b. Warm
    c. Slightly warm
    d. Neutral
    e. Slightly cool
    f. Cool
    g. Cold
10. What would you say a typical indoor temperature range is/was in winter and summer time?
    a. Answer for example 13 °C – 16 °C in winter and 24 °C – 27 °C in summer, or I don't know.
11. Any other natural building or other comfort related comments can be written below
    a. …

11 References

[1] J.C. Morel, A. Mesbah, M. Oggero, P. Walker, 'Building houses with local materials: means to drastically reduce the environmental impact of construction Building and Environment, Issue 10, pp. 1119 - 1126, Dec. 2010.

[2] D. W. Aia and A. Bertaud, 'Indigenous architecture as the basis of house design in developing countries: A case study evaluation of traditional housing in Bhutan', *Habitat Int.*, vol. 1, no. 3, pp. 207–217, Jan. 1976.

[3] Planning Commission Royal Government of Bhutan, 'Ninth Plan Report', Jun. 2002.

[4] The Engineering Adaption & Risk Reduction Division, *Bhutan Green Building Design Guidelines*. Thimpu, Bhutan: The Engineering Adaption & Risk Reduction Division within the Department of Engineering Services of the Ministry of Works and Human Settlement, 2013.

[5] M. Dujardin, 'Bhutan's human settlements sector: dynamics of tradition and modernity', *Bhutan Asp. Cult. Dev.*, pp. 137–171, 1994.

[6] Department of Renewable Energy and Ministry of Economic Affairs, 'Bhutan Building Energy Efficiency Study, Part 1 (Main Report)', Department of Renewable Energy.

[7] G. Minke, *Building with Earth, Design and Technology of a Sustainable Architecture*, 3rd ed. Basel: Birkhäuser, 2012.

[8] National Renewable Energy Laboratory (NREL), *EnergyPlus*. 2018.

[9] 'Bhutan | Data'. [Online]. Available: https://data.worldbank.org/country/bhutan. [Accessed: 11-May-2019].

[10] A. Hoy, O. Katel, P. Thapa, N. Dendup, and J. Matschullat, 'Climatic changes and their impact on socio-economic sectors in the Bhutan Himalayas: an implementation strategy', *Reg. Environ. Change*, vol. 16, no. 5, pp. 1401–1415, Jun. 2016.

[11] B. Mayhew and L. Brown, *Lonley Planet Bhutan*, 6th ed. Lonely Planet Publications Pty Ltd, 2017.

[12] Ministry of Work and Human Settlement, Royal Government of Bhutan, 'Bhutanese Architecture Guidelines', Ministry of Works and Human Settlement, Thimpu, Bhutan, 2014.

[13] National Statistics Bureau and Royal Government of Bhutan, *Bhutan Living Standards Survey Report 2017*. Thimpu, Bhutan: National Statistics Bureau of Bhutan, 2017.

[14] N. Lechner, *Heating, cooling, lighting. [Elektronisk resurs] sustainable design methods for architects.* Hoboken : John Wiley & Sons, 2015, 2015.

[15] Bureau of Indian Standards, 'Improving Earthquake Resistance of Earthen Buildings - Guidelines', New Delhi, Oct. 1993.

[16] G. Williams and P. McIntosh, *A Guide to Green Building*. Long Way Home, 2019.

[17] 'Conserving Traditional Bhutanese Architecture'. [Online]. Available: http://www.bhutantimes.com/article/conserving-traditional-bhutanese-architecture. [Accessed: 29-Dec-2018].

[18] African Organisation for Standardisation and Southern African Development Community, 'SADC ZW HS 983:2014'. The Standards Association of Zimbabwe, 2014.

[19] D. Ciancio, P. Jaquin, and P. Walker, 'Advances on the assessment of soil suitability for rammed earth', *Constr. Build. Mater.*, vol. 42, pp. 40–47, 2013.

[20] V. I. Osipov, 'Structural bonds and the properties of clays', *Bull. Int. Assoc. Eng. Geol. - Bull. Assoc. Int. Géologie Ing.*, vol. 12, no. 1, pp. 13–20, Dec. 1975.

[21] A. Laborel-Préneron, J. E. Aubert, C. Magniont, C. Tribout, and A. Bertron, 'Plant aggregates and fibers in earth construction materials: A review', *Constr. Build. Mater.*, vol. 111, pp. 719–734, May 2016.

[22] H. Danso, D. B. Martinson, M. Ali, and J. Williams, 'Effect of fibre aspect ratio on mechanical properties of soil building blocks', *Constr. Build. Mater.*, vol. 83, pp. 314–319, May 2015.

[23] S. Sangma, L. Pohti, and D. D. Tripura, 'Size Effect of Fiber on Mechanical Properties of Mud Earth Blocks', in *Recycled Waste Materials*, 2019, pp. 119–125.

[24] R. Eires, A. Camões, and S. Jalali, 'Enhancing water resistance of earthen buildings with quicklime and oil', *J. Clean. Prod.*, vol. 142, pp. 3281–3292, Jan. 2017.

[25] E. Cechova, 'The effect of linseed oil on the properties of lime-based restoration mortars', Tesi di dottorato, alma, 2009.

[26] P. Walker and Standards Australia, 'HB 195: The Australian Earth Building Handbook'. Standards Australia International Ltd, Sydney., 2002.

[27] R. Sarkar, A. Mudgal, S. Bhaskar, V. Gupta, and R. Kurar, 'A Review on Study on Effect of Various Admixtures on Geotechnical Properties of Expansive Soils', *Indian J. Sci. Technol.*, vol. 9, no. 44, Nov. 2016.

[28] M. Jamil, A. B. M. A. Kaish, S. N. Raman, and M. F. M. Zain, 'Pozzolanic contribution of rice husk ash in cementitious system', *Constr. Build. Mater.*, vol. 47, pp. 588–593, Oct. 2013.

[29] M. J. B. Moraes, J. C. B. Moraes, M.M. Tashima, J. L. Akasaki, L. Soriano, M. V. Borrachero, J. Payá, 'Production of bamboo leaf ash by auto-combustion for

pozzolanic and sustainable use in cementitious matrices', *Constr. Build. Mater.*, vol. 208, pp. 369–380, May 2019.

[30] R. Sarkar, S. M. Abbas, and J. T. Shahu, 'Geotechnical behaviour of randomly oriented fiber reinforced pond ashes available in Delhi region', *Int. J. Earth Sci. Eng.*, vol. 5, pp. 44–50, 2012.

[31] P. Marais, J. Littlewood, and G. Karani, 'The Use of Polymer Stabilised Earth Foundations for Rammed Earth Construction', *Energy Procedia*, vol. 83, pp. 464–473, Dec. 2015.

[32] I. I. Akinwumi, A. H. Domo-Spiff, and A. Salami, 'Marine plastic pollution and affordable housing challenge: Shredded waste plastic stabilized soil for producing compressed earth bricks', *Case Stud. Constr. Mater.*, vol. 11, p. e00241, Dec. 2019.

[33] T. B. Katwal, 'Multiple Cropping in Bhutanese Agriculture - Present Status and Opportunities', presented at the Regional Consulative Meeting on Popularizing Multiple Cropping Innovations as a Means to raise Productivity and Farm Income in SAARC Coutries, Peradeniya, Kandy, Sri Lanka, 31st of October.

[34] Ministry of Agriculture and Forest, 'The Draft 11th Five Year Plan In: Agriculture', Policy & Planning Division, Ministry of Agriculture and Forest, Thimpu, Bhutan, 2011.

[35] L. B. McCarty, L. R. H. Jr, and V. Quisenberry, *Applied Soil Physical Properties, Drainage, and Irrigation Strategies.* Springer International Publishing, 2016.

[36] Q.-B. Bui, J.-C. Morel, S. Hans, and P. Walker, 'Effect of moisture content on the mechanical characteristics of rammed earth', *Constr. Build. Mater.*, vol. 54, pp. 163–169, Mar. 2014.

[37] M. F. Jentsch, C. Kulle, T. Bode, T. Pauer, A. Osburg, Tezin, K. Namgyel, K. Euthra, J. Dukje, K. Tenzin, 'Field study of the building physics properties of common building types in the Inner Himalayan valleys of Bhutan', *Energy Sustain. Dev.*, vol. 38, pp. 48–66, Jun. 2017.

[38] DIN-Normenausschuss Bauwesen (NABau), 'DIN 4108-4:2017-03 Wärmeschutz und Energie-Einsparung in Gebäuden – Teil 4: Wärme- und feuchteschutztechnische Bemessungswerte'. 2017.

[39] M. Hall and D. Allinson, 'Assessing the effects of soil grading on the moisture content-dependent thermal conductivity of stabilised rammed earth materials', *Appl. Therm. Eng.*, vol. 29, no. 4, pp. 740–747, Mar. 2009.

[40] H. Viitanen, 'Moisture conditions and biodeterioration risk of building materials and structure', 2011.

[41] G. Calatan, A. Hegyi, C. Dico, and C. Mircea, 'Determining the Optimum Addition of Vegetable Materials in Adobe Bricks', *Procedia Technol.*, vol. 22, pp. 259–265, Jan. 2016.

[42] L. Miccoli, U. Müller, and P. Fontana, ‘Mechanical behaviour of earthen materials: A comparison between earth block masonry, rammed earth and cob’, *Constr. Build. Mater.*, vol. 61, pp. 327–339, Jun. 2014.

[43] National Research Institute for Cultural Properties and Department of Culture, Ministry of Home and Cultural Affairs, ‘Study on the Conservation of Rammed Earth Buildings in the Kingdom of Bhutan’, National Research Institute for Cultural Properties, Tokyo, Mar. 2015.

[44] X. Dong, V. Soebarto, and M. Griffith, ‘Achieving thermal comfort in naturally ventilated rammed earth houses’, *Build. Environ.*, vol. 82, pp. 588–598, Dec. 2014.

[45] I. Hegediš, N. Đurić, A. Čeh, G. Karaman, D. Vunjak, and E. Tenji, ‘Application of earth and straw mixtures in modern building’, *Arh. ZA Teh. Nauk. Tech. Sci.*, vol. 1, no. 15, Nov. 2016.

[46] V. Sharma, H. K. Vinayak, and B. M. Marwaha, ‘Enhancing compressive strength of soil using natural fibers’, *Constr. Build. Mater.*, vol. 93, pp. 943–949, Sep. 2015.

[47] S. Sasui, W. Jinwuth, and S. Hengrasmee, ‘The Effects of Raw Rice Husk and Rice Husk Ash on the Strength and Durability of Adobe Bricks’, *Civ. Eng. J.*, vol. 4, no. 4, pp. 732-742–742, May 2018.

[48] L. Greenspan, ‘Humidity fixed points of binary saturated aqueous solutions’, *J. Res. Natl. Bur. Stand. Sect. Phys. Chem.*, vol. 81A, no. 1, p. 89, Jan. 1977.

[49] Nederlands Normalisatie Instuut, ‘NEN-ISO 9869-1:2014 Thermal insulation - Building elements - In-situ measurement of thermal resistance and thermal transmittance - part 1: Heat flow meter method’. Nederlands Normalisatie Instuut, 2014.

[50] Robert McNeel and Associates, *Rhinoceros 3D*. USA: Robert McNeel & Associates.

[51] Algorithmic Modelling for Rhino, *Grasshopper*. 2014.

[52] M. Sadeghipour Roudsari and M. Pak, *Ladybug: a parametric environmental plugin for grasshopper to help designers create an environmentally-conscious design.* 2013.

[53] Eurpean Committe for Standardization, ‘Building materials and products - Hygrothermal properties - Tabulated design values and procedures for determining declared and design thermal values (ISO 10456:2007)’. Dec-2007.

[54] Deutsche Bundesstiftung Umwelt, ‘Grundlagen zur bauaufsichtlichen Anerkennung der Strohballenbauweise- Weiterentwicklung der lasttragenden Konstruktionsart und Optimierung der bauphysikalischen Performance’. Fachverband Strohballenbau.

[55] W. H. Knoll, E. J. Wagenaar, and A. M. van Weele, *Handboek Installatietechniek*, 2nd ed. Rotterdam: Stichting ISSO, January.

[56] M. P. Kshirsagar and V. R. Kalamkar, ‘A comprehensive review on biomass cookstoves and a systematic approach for modern cookstove design’, *Renew. Sustain. Energy Rev.*, vol. 30, pp. 580–603, Feb. 2014.

[57] T. Kalamees, ‘Air tightness and air leakages of new lightweight single-family detached houses in Estonia’, *Build. Environ.*, vol. 42, no. 6, pp. 2369–2377.

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