Indigenous materials in modern buildings

for low energy houses in West Africa

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ABSTRACT

Burkina Faso is one of the poorest countries in the world. This landlocked country in the west has an extremely warm climate. Temperatures over 45°C are not uncommon and there is an almost constant need to keep the building cool to maintain a temperate indoor climate.

Today there are two types of buildings being constructed in Burkina Faso; traditional clay buildings and the more modern houses made of cement bricks and metal roofs. The cement brick walls have a U-value of $3W/m^2K$ and combined with the metal roof they form a building envelope that cannot protect well against the outside heat. Either the interior becomes uncomfortably warm or the air-condition load is high and expensive. Air-conditioning overloads the power grid and the power outages are daily occurrences during the hot season.

This thesis examines, through laboratory experiments, the thermal and mechanical properties that can be obtained by vibrating clayey soil and mixing it with water, lime or cement and organic fiber (Bissap). Appropriate literature has been studied and field visits have been conducted in order to understand the difficulties of building with clay. The report examines different building projects utilizing local materials, both of a traditional and more modern nature.

Extremely little energy is required to form a building material of soil and the negative environmental impact is negligible compared to that of concrete and steel. Soil can be used in constructing houses but it is sensitive to water, something that has to be considered when designing a building. The heat conductivity is too high to provide adequate insulation for a passive house so an extra layer of insulating material is required.

The experiments performed during this project were inconclusive so it is impossible, from the results in this paper, to say if vibration is a good method for forming a building material of soil. The high water content needed, is however a major problem, shrinkage was about 20% and cracks were hard to avoid. Further investigations into the subject is necessary.

Key words: Natural building, Clay building, Earth Building, Ecological building, Low energy building, Passive house, West Africa, Burkina Faso, Ouagadougou

SAMMANFATTNING

Burkina Faso är ett av de fattigaste länderna i världen. Som ett kustlöst land beläget i Västafrika har det ett extremt varmt klimat. Temperaturer över 45°C är inte ovanligt och det är ett nästan konstant behov av att kyla byggnader för att behålla ett behagligt inneklimat.

Idag byggs det två typer av byggnader i Burkina Faso; de traditionella lerhusen och de mer moderna husen med väggar av cementstenar och plåttak. Cementväggarna har ett U-värde på 3W/m^{2}K och tillsammans med plåttaket så bildar det ett undermåligt klimatskal utan möjligheter att skydda mot hettan. Det leder idag till endera ett obehagligt varmt inneklimat eller en hög och kostsam energianvändning av luftkonditionering. Överbelastningen på elnätet på grund av luftkonditionering är påtaglig under den varmaste säsongen med frekventa strömavbrott till följd.

Denna rapport undersöker via laboratorieexperiment vilka termiska och mekaniska egenskaper man kan erhålla genom att vibrera lerjord och blanda med vatten, organiska fibrer samt kalk och/eller cement. Litteraturstudier och fältbesök i Burkina Faso har gjorts för att undersöka och förstå vilka svårigheter som kan uppkomma genom att bygga med lera. Rapporten tar även upp konkreta exempel på byggnader i Burkina Faso gjorda av lokala material, historiska såväl som moderna projekt.

Lerjord behöver extremt lite energitillförsel för att bilda ett byggmaterial och den negativa miljöpåverkan är försumbar jämfört med betong och stål. Det kan användas för att bygga energisnåla hus men det är känsligt mot vatten, vilket måste beaktas noga under projekteringen. Värmeledningsförmågan är för hög för att vara tillräcklig som isolering för att erhålla ett inneklimat enligt dagens standard, utan tillförsel av energi, så någon form av extra isolering krävs.

Experimenten som gjordes gav inte tillräckligt exakta resultat för att visa om vibrering är en bra metod att göra byggmaterial eller inte. Den höga vattenhalten som krävs för vibrering är ett stort problem. Krympningen var ungefär 20 % och sprickor var svåra att undvika. Vidare studier på området rekommenderas.

Nyckelord: Naturligt byggande, lerbygge, ekologiskt byggande, lågenergihus, Västafrika, Burkina Faso, Ouagadougou

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1 INTRODUCTION

Burkina Faso is a country on the African continent. It is located in the west of Africa and shares borders with the Ivory Coast, Benin, Ghana, Niger and Mali. The climate is hot and sunny and as a landlocked country it has great variations in temperature. During the warm period in April and May temperatures can rise up to over 45°C (Landguiden.se 24/5-2013). During most of the year it is warmer outside than can be considered a comfortable indoor climate (APPENDIX1)

In the modern building design of Burkina Faso, little to no attention is being paid to the thermal envelope and energy efficiency (Toguyeni et al, 2012). Africa consists of many different countries with different types of climate. As part of the Sahel region in the outskirt of Sahara, Burkina Faso is one of the warmest parts of the continent with around 94 000 cooling degree hours per year ("Roof insulation" Toguyeni et al 2012). This can be compared to the 105 000 heating degree hours per year that Lund, Sweden has (Sandin, 2010)

The need to find new, cheaper and more environmentally friendly building techniques and to construct better insulated houses is obvious. In an extremely poor country such as Burkina Faso, the question is how.

In a conference in Stockholm, Didier ROUX (12 March 2013), President of innovations at Saint-Gobain, talked about building materials of the future. He maintained that it is important to look at the building materials and techniques that have been developed during thousands of years. Even if the benefits are not yet scientifically proven it does not mean they do not exist. He said that Saint-Gobain is doing research on the extremely thin ice-membrane that is being created inside igloos and how clay buildings have phase-changing properties that can lower the inside temperature even when the outside air is extremely hot.

There are many reasons for investigating whether clay can be used in modern buildings. It is found virtually everywhere in the world. One third of the world's population live in buildings made directly from the soil. There are many positive aspects of using clay in construction. It is cheap and the negative environmental effect is basically zero in a global perspective and extremely low on the local surroundings. Despite widespread use and long tradition, however, it is not usually regarded as an option when constructing new buildings. There are several reasons for that. Engineers are careful in using a material that is hard to standardize, the properties of the clay have to be investigated each time. It is labor intensive and the social aspect is very important since clay is often not regarded as a material for the modern successful person. (MINKE, 2006)

Recently collaboration between Sweden and Burkina Faso has been initiated to investigate the possibilities of using clay as a building material in a modern building.

1.1 Project description

In the spring of 2013 ISP, International Science Program, decided to support a multidisciplinary project at the Laboratoire de Physique et Chimie d'Environement (LPCE) at the University of Ouagadougou, Burkina Faso. The project will run for at least three years and during those years several issues will be investigated and the result will be a completely functional building, mainly made of local and sustainable building materials and where a comfortable indoor climate is maintained without the need of an external source of energy. The goal is to show the residents of Ouagadougou and all other Burkinabé (the citizens of Burkina Faso) that there are alternatives to the energy intensive buildings that are being erected today in Burkina Faso.

1.2 Purpose and Aim

The purpose of this thesis is to lay the groundwork for further study into the field of constructing a low-energy house with local materials.

Specific goals have been:

1) To see if vibration can be used as a method for constructing building elements out of clayey soil,

2) To determine the thermal and mechanical properties of the soil in Burkina Faso, when combined with organic fibers, cement, and/or lime and then vibrated,

3) To examine the traditional and modern building techniques of Burkina Faso,

4) To investigate and analyze modern attempts of building with soil,

5) To investigate which cooling systems can be appropriate for buildings in Burkina Faso.

1.3 Method and material

The author has spent two months in Burkina Faso, working at the Laboratoire de Physique et Chimie d'Environement (LPCE) to determine the mechanical and thermal properties of vibrated soil as a building element.

During the stay, interviews and field visits were made to understand the building culture of Burkina Faso. Both traditional buildings with indigenous building materials and modern building with imported materials have been studied. Field visits were also made to several sites where modern buildings have been erected using soil in different ways as the main building material.

Back in Sweden a literature study has been made on previous work within this field.

1.4 Disposition

Chapter 1	Introduces the subject and gives a background to the Swedish collaboration in Burkina Faso.
Chapter 2	Gives a background and explains the topic of the report and its actual relevance. Description of the country and its building culture. An introduction of earth as a building material is also included
Chapter 3	Explains the laboratory work of the study, how the specimens were made and how they were later tested and measured.
Chapter 4	Lists the results from the thermal and mechanical testing. Also explains the practical result from using vibration to make the specimens.
Chapter 5	Discusses and reflects on the result.
Chapter 6	Gives suggestions on continuing research within the subject.

2 Background

2.1 Burkina Faso

Burkina Faso is a country in West Africa, Figure 1. As a part of the Sahelian belt on the southern border to the Sahara desert, temperatures can be extremely high, temperatures above 45°C are common. (Landguiden.se 24/5-2013) (Ingram et al 2002). The country consists of different regions; the Sahelian region in the north, on the border to Sahara, where it is almost desert-like (semi-arid) with very limited rainfall (as little as 150mm/year); the further to the south the more the rainfall and on the border to Ivory Coast there is a sub-humid climate with 6 months of rain with more than 1000mm/year (MANSON & KNIGHT, 2006, P.3-5)

During the last three decades, the Sahelian region has experienced decreasing rainfall and increasing temperatures. A trend that according to the International Panel on Climate Change (IPCC, 2001) will continue, leading to two to five degree increase in mean temperature in Africa during this century, and the biggest effect will be experienced in the region of Burkina Faso. (DESANKER et al 2001)

Figure 1 - Burkina Faso, on the southern border of the Sahara desert.

Burkina Faso has three seasons: a hot season from March-April, a rainy season from June - September and a dry season from October – February (Ouagadougou). Although the rainfall, and to some extent the temperature, can vary, depending on location in Burkina Faso, the temperature is almost always warmer than what is considered a comfortable indoor climate (MANSON & KNIGHT, 2006, P.3)

Burkina Faso has a population of 17 million of which 26% live in cities. The largest city is the capital Ouagadougou which is located in the densely populated center of the country. There is a high rate of migration to Ouagadougou from the surrounding countryside and in 2012 the city had an estimated population of 1.67 million. (Landguiden.se 2013-05-26)

The country has a high mortality rate of 12/1000 (2011) and a life expectancy of 54 years for men and 56 years for women. A high birthrate leads to a high annual population growth rate of 3% (2010). The financial growth rate has been good during the 21st century but the growth in population has eaten up the main part of it, so the living standard for most people has not improved. (Landguiden.se, 24/5-2013)

Burkina Faso is an old French colony that achieved its independence in 1960. The official language is French but there is a number of regional languages in the country were the Mossi tribe's language Moré being the most common. (Landguiden.se) It is not unusual for a Burkinabe to speak two, three, or even four different languages fluently.

Burkina Faso has a very modest indigenous energy production, which means that energy is imported at high cost and all the energy that can be saved is of great importance.

Air conditioning in the sub-Saharan countries requires about 250-450 W/m^2 (TOGUYENI et al, 2012), which in turn is difficulkt for Burkina Faso to handle due to an unsufficient power grid and limited domestic electricity production. Importing expensive electricity from Ivory Coast and other countries is a necessity in order to maintain the power grid. Despite the import of electricity, daily power-cuts are not uncommon.

Burkina Faso is one of the poorest countries in the world; with a GDP per capita of US$639 US dollar. More than half of the population lives on less than one dollar per day (Landguiden.se 24/5-2013) meaning most people cannot afford air conditioning. In 2001 The United Nations controlled IPCC (International Panel on Climate Change) released a report (DESANKER et al 2001, P.499) determining the following about heat related mortalities in Africa:

"there is a need to consider building technology and building materials' thermal properties to produce dwellings that are naturally climatically comfortable for tropical conditions".

Insufficient natural ventilation is in the report mentioned as a major problem. Polluted air another.

In the same report DESANKER lists a few areas that are of extra importance when facing the global warming. Two of them are:

- *Intensive research into energy usage and alternate renewable energy at household and industrial levels*
- *Innovation in building designs*

2.2 Building with earth

This chapter discusses different aspects of using soil as building material and illuminates previous research in the area.

2.2.1 Previous research

Today, one third of the world's population live in buildings made directly from the soil and in developing countries it is half of the population. Despite that, very little scientific research has been done in the field of building with local soil. Especially compared to what we know today about the properties of steel and concrete. (JAQUIN, 2009)

In order to build with earth it is of great importance to know the properties of the soil. To identify the soil, a laboratory may be required. Apart from that, traditional craftsman skills and local knowledge are of great significance. (ZAMI, LEE 2008, P.49)

MINKE (2006 p.44) writes the following about the knowledge of mechanical properties of earth as building material:

> "*The compressive strength of a mix is affected by the type and amount of preparation, as well as by the proportion of water used in the preparation, a fact that is neither well-known nor well-researched.*"

JAQUIN (2009) writes that, during the last three decades there have been some ambitious experiments to improve earth-building techniques and to obtain a better understanding of the properties of earth building. According to JAQUIN however, these have been poorly documented and there remains much to be understood at a scientific level regarding earth as a building material.

2.2.2 Definition

In this report as well as in other publications in this area the words earth, soil, clay and loam will be used. It may be difficult to understand the exact meaning of these terms. What is the composition of the earth/soil/loam/clay? This is a valid question and for the purpose of this paper the following definition is given.

Building with earth/soil/loam/clay means the use of suitable soil, found in close proximity to the building site, as building material for the house to be constructed. That soil is sometimes used directly without any preparation but usually there is some kind of tampering with the soil in order to enhance its properties. This can entail adding water for workability, lime for strength or organic fibers for insulation. This can be done in countless combinations. However, if the material is burnt or heated to high temperatures to change its chemical structure it is not usually considered in this category. Concrete and baked bricks are for that reason not considered as earth building even if the material from the beginning comes from the earth.

2.2.3 Why earth building?

Although there are question marks about how much the global mean temperature will rise in the future, the scientists of the world are united in the belief that we are experiencing a global warming that will not slow down unless emissions of green house gases (GHG) is lowered (IPCC 2011). At the same time the world's population is rapidly growing and a conservative estimate is that by the end of this century the population of the earth will exceed nine billion (Rosling, 2013)

The quantity of new constructions will have to dramatically increase leading to a shortage in both conventional material resources and energy supply. (MINKE, 2006) The industrial building materials of today are great contributors to the environmental problems the world is facing (KENNEDY et al, 2002 p.2). The lowest estimations say that the production of cement alone (not concrete) stands for more than 3% of global GHG. About half comes from transportation and half comes from the energy-intensive heating process that is needed to make cement. Other research shows numbers up to 10% (REHAN & NEHDI, 2005 P.106)

In Burkina Faso, this is not merely a global problem for the future. Much of the building material is imported at high cost and with a rapidly increasing population the problems with sufficient dwellings already exist.

Building with local earth eliminates many of the problems. The material is found locally so there is hardly any transportation cost and the material is sun-baked so there is almost no energy demand in the production. When talking about the earth building techniques compared to modern industrialized concrete houses ZAMI & LEE (2008) writes

"Such techniques of using soil have distinct advantages, such as eco-friendly, recyclable, economical, and better thermal comfort."

Building with earth is labor intensive, (MINKE 2006) something that works well in an economy like Burkina Faso's where man-hour labor is relatively cheap. MINKE also writes,

"The preparation, transport and handling of loam on site requires only ca. 1% of the energy needed for the production, transport and handling of baked bricks or reinforced concrete. Loam, then, produces virtually no environmental pollution."

Clay walls tend to be sensitiv against intense water penetration. Degradation can occur if rain penetrates the surface. Many times this is the reason that clay is rejected as a modern building material. However with good protection from a roof with adequate overhang, walls can remain intact (Jaquin, 2009)

2.2.4 Clay - a special binder

Clay is defined as the particles in soil that are smaller than 0,002 mm. Clay has a very significant difference compared to larger fractions such as silt or gravel. The binding force in the larger fractions mainly comes from friction while in clay it mainly comes from electro-chemical binding. (BURSTRÖM, 2001) The particles in the clay consist of silicates and aluminates formed in parallel layers and is one of the binding reagents in cement and hydraulic lime. Hydrated lime can become hydraulic by adding clay. (DE BRUIJN, 2012)

The binding force of the elements is related to the specific surface of the mineral and the clay particles can be divided into two-layered particles called Kaolinite and three-layered particles called Montmorillonite. Montmorillonite has a much greater specific surface and therefore has different properties than Kaolinite i.e. the cohesive force is stronger when the specific surface increases. As a reference to the difference in surface it should be said that sand has a specific surface of around 23cm^2/g, silt about 450 cm^2/g, Kaolinite about 10m^2/g and Montmorillonite about 1000m^2/g. (MINKE, 2006)

2.2.5 Building techniques

Traditional building techniques can be divided into a few different genres.

Adobe

Adobe bricks are handmade, sunbaked, bricks made of clayey soil mixed with water and sometimes cut fibers. The fibers work as reinforcement and also even out the drying process. (Lerbyggeföreningen.se, 2013-05-25) The bricks are made by throwing the mixture into a wooden mold and then leaving it to dry. After drying these bricks are then used together with mortar joints to construct walls Figure 2 The joints are preferably made of the same material as the bricks. One person can make about 300 adobe bricks per day.

The harder the throw the better mechanical strength is achieved. Since it is impossible to know the velocity of a somatic throw in advance, it is also hard to define the properties of the building element. That prohibits a standardization of adobe bricks. MINKE (2006)

Figure 2 - Adobe house in central Burkina Faso

Rammed earthwork

This is an on-site technique that uses a formwork similar to the formwork of on-site casted concrete walls. The moisture/watered soil is pressed into the formwork. As opposed to the method of casting concrete, the rammed earth form is not as high as the wall. To be able to compress the soil, the rammed earthwork form is only around half a meter high. When the soil has been compressed, the formwork is moved, higher and higher. (MINKE 2006 P.52)

Wet Loam Stacking (COB)

As in the case of the rammed earthwork, walls made with wet loam stacking are made directly on site. Instead of using a formwork, balls of clay mixed with water are simply pressed against each other in the wall. A layer is made and left to dry before continuing higher up the wall. (Figure 3)

Figure 3 Kasena house in southern Burkina Faso made with wet loam stacking

Compressed earth bricks (CEB) (Unbaked bricks)

Ever since the first known mechanical press driven by somatic force was invented in France in the 18th century by the French architect François COINTREAUX there have been many attempts to improve that technique. (MINKE 2006 P.63)
The mechanical compaction which leads to higher density has great positive effect on the compressive strength of the brick and its resistance to water *(CRATerre: Compressed Earth Block: 1991)*

According to MINKE (2006 P.44) this is not a general truth. When it comes to loam and its strength it is important to understand the microstructure of clay and where its strength comes from. The clay minerals have a lamellar structure (2.2.4) and its plasticity comes from when the smallest particles in the soil (Thickness 0,03, Length 0,5μ) are surrounded by a thin layer of water and at the same time the particles have electro-chemical attraction to one another.(BURSTRÖM, 2001 P.337) (MINKE, 2006, P.21,P.44) That attraction is activated by movement. The dynamic movement, like throwing loam into a mold (adobe), makes the lamellar wet particles sort themselves in a parallel composition, which in turn gives a more efficient compression and tensile strength to the material when dried. Experiments at the Institute for Building Technology of the Swiss Federal Institute of Technology in Zurich showed an average of 19% increased strength of a handmade adobe compared to a brick mechanically compressed with a force of 20kg/cm^2 (MINKE 2006 P.44)

Due to the lack of dynamic compression, the mechanically compressed earth brick is often stabilized with 4-8% cement in order to achieve sufficient properties of strength. The need for a high-energy binder is questionable in terms of ecological building and many earth-builders consider cement as a non-option. (Sutton et al 2011)

Pierre Taillé

Pierre Taillé (cut stone eng.trans.) is a soft rock mineral. It has a reddish color from its rich content of iron. When the stone is taken from the ground it is relatively soft but as the iron oxidizes, in contact with air, the stone grows harder and harder for each year. Pierre Taillé is used to build walls instead of the hollow cement bricks. It can be found locally and it is a resource that requires relatively little energy to be converted into a construction element. Experiments have shown that lime mortar works well with the Pierre Taillé. (Figure 4)

Figure 4 - House made of Pierre Taillé under construction in Ouagadougou

Mortar joints

Building with bricks, whether green bricks made of clay or cement bricks, is usually done with some kind of mortar joint between the bricks in order to get an even compression on every brick. It is of great importance to pay attention to what kind of mortar is used. A cement-based mortar does not work well with clay. Clay-based mortar and cement-based mortar react very differently with varying moisture content and a cement-based mortar does not form a good bond with a clay brick. (Sutton et al, 2011)

2.3 Low energy buildings

A Passive House is a building, in which thermal comfort (ISO 7730) can be provided solely by postheating or postcooling of the fresh air flow which is required for good indoor air quality (DIN 1946) - without using recirculated air in addition

In buildings where people work, live and sleep, there is an endeavour of keeping the temperature at an even and comfortable level. (BURSTRÖM, 2001) Because the outside temperature varies, there will usually be a heat transfer between the outside and the inside. Unless the outside temperature is at a perfect steady level, a cooling or heating system, depending on if it is warmer or colder than desired outside, is required to maintain the comfortable indoor climate. Since such a system requires energy it is preferable to minimize the heat transfer. Something that can be done by making the building envelope well insulated and airtight so there is perfect control of the airflow. If that is done properly it is possible to install heat/cooling recovery on the ventilation system. A passive house takes this technique to such a level that no or very little external energy demand is required.

In northern Europe it has become increasingly popular to construct buildings according to the passive house standard. Some houses have performed so well that together with photovoltaic cells on the roof, the building produces more energy than it consumes.

According to LEVINE et al (2007 P.395) it is possible, by improving the thermal envelope, to decrease the cooling energy demand, for a building in a hot climate, by a factor 2-4, something that can be done at very little to no added incremental cost. Hans EEK, expert on passive houses in Scandinavia, believes the factor can be as much as 5-10 times.

An important part of a sustainable and energy efficient building is that the building is adapted to the geographical location and climate. (SCHMITZ-GÜNTER 2000 P.) However this is not usually a consideration in modern building (LEVINE et al 2007 P.397) (BOKALDERS, BLOCK, 2009, P.376) Using local materials forces the builder to automatically pay attention to the local aspects (JOSEPH et al, 2002, P.6) If natural ventilation is being used instead of mechanical it is even more important to consider the local aspects.

2.4 Building Culture in Burkina Faso

The buildings in Burkina Faso can be divided into two different general types of constructions, one old version with clay walls and a clay or straw roof (still being built to some extent in the countryside) and one new with concrete bricks for the wall and a simple uninsulated metal roof (mainly built in cities). During the last decades a mix of these two types have been growingly popular in the countryside with clay walls and a metal roof.

Figure 5 - This was the last area in Ouagadougou people still lived in clay houses. It was demolished and the people living there were moved a few years ago to make room for more modern buildings of concrete

2.4.1 Traditional Clay building

There are many different ethnic groups in Burkina Faso. Each of these groups has their own way of building their traditional homes. In the south of Burkina Faso on the border to Ghana you can find the Kasena houses with their flat clay roofs and aesthetically ambitiously painted facades (Figure 6) In the central part of Burkina Faso, the Mosi people build more subtle homes with clay bricks and straw roofs (Figure 7)

One thing that basically every traditional building technique in West Africa has in common is that dried, but unfired, clay is used to construct the walls (MINKE, 2006). Clay is everywhere in Burkina Faso and that makes it a very cheap building material with a low energy impact (SUTTON et al, 2011). The energy required to build with fired bricks or reinforced concrete is more than 100 times higher than if the same building is constructed with local loam. That includes production, transportation and handling (MINKE, 2006, P.14).

Kasena houses
Unless otherwise noted the information about the Kasena houses comes from the Tiebele resident and local expert Aziz SANA, at a field visit in Tiebelé 24/3-2013.

The Kasena houses are built in two different ways, the wet loam technique and the adobe technique. Both types of building have relatively cool indoor climates and have the ability to even out diurnal temperature differences. When the outside temperature reaches 45-50°C in the shade, it is still around 30°C inside the building.

Wall – Wet loam
Building with the wet loam technique means that you mix water and loam and build the walls on-site by using your hands to shape the clay into a wall (MINKE, 2006). The houses are distinctly noticeable due to their round shapes. First the house is built to a height of a few decimeters. After a wait of several days for drying the process of building the walls continues. It takes about one month to complete a two-room house. It is usually the elderly people that build the houses when the younger are out working.

The wall is relatively thin, around 15 cm and very strong. The wall is monolithic and therefore has longer life durability than the adobe technique (MINKE, 2006). According to Aziz Sana, the oldest buildings in Tiebele are from 1640 A.D.

Wall - Adobe
During the last hundred years, another type of building has become more and more popular; the adobe technique. It is easy to tell the difference from the wet loam houses since the adobe houses are rectangular and have significantly thicker walls. The adobe technique entails mixing water and loam in the same way as mentioned above. However in this case the loam is manually compressed into a wooden mold that is removed immediately after compression. The newly formed loam brick is then dried in the sun for several days. After the adobe bricks have dried they are brought to the construction site and used in the same way as kiln-fired bricks just like a masonic wall. The joints are made of loam and water, just as the bricks. After the walls are finished, plaster is applied to the wall surface. Also made of the same loam.

Building with adobe is significantly faster than the wet loam technique. It takes about 5-6 days to finish the walls of a house with adobe bricks compared to building a structure of the same size using the wet loam technique, excluding the time necessary to make the bricks.

Roof

The roof is basically the same on the cob and the adobe house. The only difference is the geometrical surface. It consists of three layers. The lower layer bears the weight of the roof and is constructed of branches of varying dimensions laid crosswise until the layer is 20-25 centimeters thick. The second layer is as thick as the first and is comprised of the same loam as the walls It is laid on the branched roof and then stomped/compressed with wood sticks. The top layer is much thinner and forms the water-resistant surface. It is 3-5 centimeters thick and made of "terre rouge" or red sand. When terre rouge is mixed with water and then dried it becomes very and durable, by appearance similar to concrete. The Kasena houses have no windows but they have one hole in the roof of each room which functions as a source of light and at the same time provides ventilation.

The roof is generally the most vulnerable and exposed part of a building and the Kasena roof is no exception. The roof is completely replaced every 5-6 years but it is not due to mechanical or chemical deterioration from rain, wind and sun, which is usually the case with roof problems. The reason it is being frequently replaced is because of termites that eat up the load bearing wood structure. Since these houses are being built directly on the ground there is no protective barrier against the termites coming from the ground and climbing up the walls.

a) b)

Figure 6 – a) Kasena House made of wet loam
b) Kasena house made of adobe

Mosi houses – central Burkina Faso

In modern Mosi villages, two types of buildings can be observed; one round with a conical straw roof and one rectangular with an almost flat metal roof. In contrast to the Kasena houses, the Mosi people do not build several rooms in a building. They build several one-room houses and then unite them with a wall so it becomes an enclosed area. Many times you can see both types of architecture in one enclosure.

The older construction with a straw roof provides a fairly good indoor climate with reasonable temperatures. The modern type with a metal roof works almost like a solar collector and the temperature inside during the hot period can be extremely high. (Lennart Karlsson (5/4 2013). Eva Karlsson (6/4 2013) who has visited and lived in the Mosi villages of Burkina Faso during more than two decades and seen the transition from straw to metal roof buildings says that more and more people sleep outside during the hot period because the indoor temperature is unbearable.

Walls

Both the round and rectangular buildings are made of adobe blocks in the same fashion as the modern Kasena buildings. Half-completed walls may often be observed un Mosi villages. This is due to the cost of construction material. Villagers build their homes in stages and pauses when they have unsufficient funds. When the masonry is finished it is time for plaster, which is loam-based just as in the case of the Kasena houses. Many times the financial situation prohibits plastering the entire house and it is not absolutely necessary either. It is of utmost importance to cover the outside façade that is most exposed to headwind and driving rain. That side is also the one that requires the most attention. With good maintenance a traditional Mosi building can stand a very long time but without proper overhaul it may break down in a few years. (Lennart Karlsson 27/4) Traditional round buildings as shown in (Figure 7) have an opening which serves as entrance, light intake and ventilation. Sometimes these houses also have a small opening for additional light and ventilation. The modern rectangular buildings will often have an added steel door and one or two small steel windows. The doors and the windows are not airtight and do not have a glass cover. They resemble oversized window blinds with mosquito netting

a) b)

Figure 7 a) Traditional round Mossi house straw roof and surrounded by an adobe wall round the residential area b) modern house with rectangular shape and metal roof

2.4.2 Modern conventional building

This section gives a short summary of how modern buildings in Burkina Faso are generally constructed. A more detailed explanation of the building procedure is found in APPENDIX 2 – MODERN BUILDING

Since Burkina Faso is a francophone country and an old protectorate of France, many European traditions have been established in Burkina Faso, and the building tradition is no exception (KARLSSON, SOUGOTI a.o.) Concrete has replaced traditional materials in the construction industry over the past decades and at present almost all modern buildings erected in cities in Burkina Faso are made according to the same principle. This entails using concrete in the foundation, building the load-bearing beam/pillar system of reinforced concrete, using cement –based bricks without rebar in non-bearing walls, applying cement-based plaster on both inside and outside and topping the structure with an uninsulated roof of corrugated sheet metal. The architecture can sometimes be creative and unique with colorful walls and large window openings but the construction method is always as mentioned above. (Figure 8)

The U-value of the cement bricks after plastering is around 2,6 W/m^{2}K (APPENDIX 3 – U-VALUE CEMENT BRICK)

Figure 8 – Modern building with cement bricks and a load bearing concrete structure. Nice facades but no attention is paid to the thermal envelop. One air-conditioning system is instead put in every room.

2.5 Modern attempts of using earth as building material

There have been a few attempts to incorporate traditional building materials such as clay into modern structure in Burkina Faso.

2.5.1 Panafrican Institut pour Development (PID)

In the late seventies the ADAUA (Association pour le Développement de l'Architecture et de l'Urbanisme en Afrique) instigated an ambitious project in Ouagadougou, the capital of Burkina Faso. The ADAUA did not regard the western model of constructing industrialized concrete buildings as a long-term and sustainable solution to building in West-Africa, and an attempt to build using local materials and techniques was initiated. The project consists of a group of architecturally impressive buildings with a total floor area of 5658m^2 made of locally produced, stabilized and compressed soil bricks (CEB or Banco in French) (MOULINE, 1992).(Figure 9 a)The buildings are full of vaults and domes and in 1992 the project was awarded the Aga Kahn Award for Architecture. (MINKE 2006 P. 174)

However, due to a variety of reasons the buildings have suffered from such degradation that they now need to be completely demolished (Figure 9 b) and rebuilt using better techniques. The new project is scheduled for completion in 2019.

Figure 9 a) PID Newly built (1984)
[b) Under demolition (2013) in order to be reconstructed

Building technique and material.

The clay loam was taken from an area close to (within 3 km) the construction site. The bricks were compressed and stabilized using 4% or 10% cement depending on where in the structure it was used. The cement was the only imported material and it came from the neighboring country Togo. (MOULINE, 1992)

Cement is a rigid material whereas loam is more plastic/elastic and has a slight give, when the relative humidity and temperature vary. Cement does not move in in the same way which creates a gap between the two materials. Cement can be used in some cases, but it has to be used with great caution and careful research has to be made to find the right quantity and quality. In this case, time shows that the research and production was unsufficient. The banco bricks did not attach very well to the joints and surface leading to rapid degradation seen in Figure 10. Separating the joint from the brick could after less than thirty years easily be done by hand.

Clay loams are sensitive to liquid water and must therefore be protected against capillary water from the ground. (BOKALDERS, BLOCK, 2009, P.47) In the case of PID, the walls were built directly on the ground without any foundation work at all.

As early as in 1992 MOULINE writes about the degradation but according to him it is due to poor maintenance resulting from budget deficits rather than the material itself. The first years the roofs leaked during periods of heavy rainfall, a problem that was eliminated when an asphalt cover was laid on all the roofs. More pictures of the project are seen in Figure 11

a)

b)

Figure 10 a) Poor binding between plaster and banco bricks

b) No adhesion between cement based joints and banco bricks

Figure 11 PID – Beautiful architecture but rapid and severe degradation

2.5.2 Musee de la Music de Ouagadougou

Another project similar to the Pan African Institute for development (PID) is the Museum for Music, located in the center of Ouagadougou (Figure 12). It opened in 1999 and received support from ADAUA (Association pour le Développement de l'Architecture et de l'Urbanisme en Afrique) the same group that built PID. It is built from compressed local earthen bricks and has a Sahelian structure of vaults and domes and small rooms going into each other (http://ouaga-ca-bouge.net/Musee-de-la-Musique-la-musique). The building has had problems with water penetrating the roof and is currently undergoing major renovations to repair the damage and improve the roof cover. The exterior of the building was completed in May, 2013. However there are still some work remaining on the interior

Figure 12 Musee de la Music de Ouagadougou

2.5.3 Sabou

In 2012 a test building was made in Sabou (Figure 13), a village in the central part of Burkina Faso. In Sabou, more and more buildings are being constructed of concrete. Some of the citizens wanted to show that it is possible to build a modern housing using traditional techniques. The building material is banco (adobe). It is not stabilized or mechanically compressed. The bricks are made using the traditional technique of throwing the loam, by hand, into a wooden mold. The mortar for the joints is made of the same loam. Nothing is added.

The house has two rooms with one bathroom each. The structure of each room is a vault. The walls have one and a half rows of banco and the vault roof consists of, from the inside and out, two layers of banco, one layer of waterproof plastic foil, one layer of banco and finally a few centimeters of manually compressed "terre rouge" as a weather protection. The banco bricks in the vault structure are much thinner than in the walls, 5 cm thick instead of 12 cm as it is for the walls.

According to the owner there have been no problem with the building, even during the rainy season the structure remained intact and no rain penetrated the roof. However, it is important to remember that this structure is only a year old. Degradation may still cause problems in the future.




Figure 13 Newly built adobe house with vault shaped roof of soil and plastic sheet. Vault openings makes lentils unnecessary.

2.5.4 Ouaga 2000 – Achante project

Ouaga 2000 (deux milles) is a suburb of Ouagadougou. It is located in the southwestern part of the capital. At present Ouaga 2000 remains isolated but is planned to be integrated with the city as the capital grows.

Achante is an organization of people who have different specialties, such as architects, engineers, economists and financial capitalists. The goal for the Achante group is to find new, sustainable ways of conducting lucrative business. For that purpose Achante has purchased a piece of land in Ouaga 2000 to experiment with constructions using local and environmentally friendly materials. The houses will later serve as model homes to show potential customers and policy makers that it is possible to build comfortable and sustainable dwellings. In this project three different models are being built. The houses are in different price categories so there are houses in the low, middle and upper income ranges.

The material that Achante is focusing on is Pierre Taillé, (Figure 14) a red, iron-rich stone that is quarried from the ground. The stone is cut to rectangular bricks and built using the same techniques as in buildings with adobe or modern concrete bricks. The joints between the bricks are a lime mortar. Cement was tried but the adhesion to the stone was insufficient. The problem also occurred with the render. The cement render did not attach well to the wall and many cracks occurred as the render dried. The lime render and joint on the other hand showed results that were better than expected and for that reason it was decided to use a lime mix for the whole project. The lime comes from Bobo Dioulasso. The Pierre Taillé is in this project also load-bearing so no concrete beams and pillars are used. (R. Sourdois, 2013)

Figure 14 House made of pierre taillé. A iron rich, red stone. It is relatively soft making it possible to carve with simple tools

2.5.5 Nakamtenga

The small village Nakamtenga is located a few kilometers outside of the city Siniare, 50 kilometers north of Ouagadougou. During the previous decade an elementary school was constructed there .(Figure 15) Lennart Karlsson is the designer and supervisor of the project. Karlsson has used different construction materials in previous projects , but the material he has found most suitable is *pierre taillé*. Accordingly, the entire school was built using *pierre taillé*, on top of a concrete slab. The project used the same beam/pillar system as the modern concrete-brick building.

Using the same beam/pillar system as in conventional building allows for a smooth transition for the craftsmen/masons, since it is basically the same building method. The only difference is that local stone instead of imported cement-bricks are used in the non-bearing structure. The surface of the Pierre Taillé wall is completely maintenance free and no plaster or paint is required. Since it contains considerable amounts of iron, it actually hardens when in contact with air. (L. KARLSSON, 2013)

Adjacent to the school KARLSSON is building a residence with ground cooling and a solar chimney for ventilation.

a)

b)

Figure 15 a) School in Nakamtenga made of pierre taillé with load-bearing structure of concrete.

b) The school from the outside

2.6 Ventilation and Cooling

In all buildings with human activity some kind of air-exchange is required to sustain a fresh indoor climate. A recommended value for residential houses in Sweden is that the total air volume is exchanged every two hours. (WARFVINGE, DAHLBOM, 2010) In warmer climates it can be an even higher frequency for cooling. There are many ways of ventilating a building. It can be done either naturally or mechanically. Natural ventilation means that you either let the wind blow through the building or you use the fact that warm air has a lower density than cold, the so called "chimney effect". The latter is preferable to use in a passive house because it is easier to control, something that could possibly be done by building a solar chimney.

There are several reasons to use natural ventilation. Studies have shown that if it is warmer outside than inside (and therefore a need for cooling), people are more satisfied with a higher temperature if the building is naturally ventilated. If the outside air is 30°C, more than 80% of the residents are content if the inside temperature is 27°C. If a mechanical air-conditioning system is used, the same satisfaction is achieved when the inside temperature is 24°C. It has also been shown that there is a 30-200% higher risk of experiencing *Sick Building Syndrome* (SBS) if the cooling is made by air-conditioning instead of natural ventilation (de DEAR, BRAGER, 2002, P.560)

2.6.1 Solar chimney

Warm air raises and the bigger the temperature difference is in a room the faster the air will raise. In a building that creates pressure differences, making the air move upwards there is natural ventilation if there is an opening in the roof. In a cold climate like in Sweden, that technique has been used for centuries to ventilate buildings. It works well in the winter but in the summer when the temperature outside can be warmer than the inside, that decreases the efficiency of the system dramatically. In a warm climate like in Burkina Faso a system like that would probably work poorly. But if the temperature on the inside of the roof could be higher than the outside temperature it would improve the efficiency of the chimney effect.

A black chimney made of metal could be the solution(Figure 16). When the sun shines on the metal, the air inside will get warmer and lighter, forcing it to go up. New air from underneath (inside) will be drawn into the chimney were it will heat up and rise, making room for new air from the inside and the process has started. If the chimneys can heat up the air fast enough this could ensure sufficient ventilation.

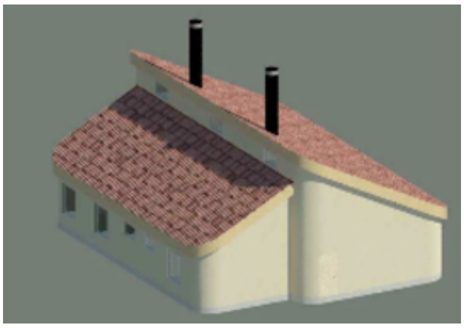


Figure 16 - House with solar chimney

2.6.2 Earth cooling

IPCC thinks that earth cooling will be one of the most important cooling techniques on the African continent. Earth cooling uses the fact that the ground has a stable and usually lower temperature than the outside air. There are many different techniques but the simplest technique is to let the incoming air pass through pipes buried in the ground (Figure 17). A project using this technique is under construction outside of Siniare. Preliminary measurements made outside of Ouagadougou shows that the temperature both one and two meters down in the ground is about 30°C during the warmest period (March-May)

Figure 17 Earth cooling, air enters the pipes and cools down before it enters the house

2.6.3 Heat driven cooling

If the earth cooling is not enough there are other alternatives to traditional air condition, they are however more complex and uses more advanced techniques.
Absorption and desiccant cooling are two techniques that use the paradox of heat driven cooling. The techniques are very different but they both uses evaporation and condensation to move heat. Absorption cooling is a closed system that works as a regular air condition but instead of a compressor there is a heat driven absorptive medium. Desiccant cooling is an open system that uses the fact the evaporation requires energy (heat), which means lowering the temperature of the incoming air. Absorption cooling works best when the latent cooling load is low and the desiccant cooling works better when the latent cooling load is high (RYDSTRAND et al, 2004). Burkina Faso has a relative humidity varying between 15% and 100% APPENDIX 1 – CLIMATE DATA but as described in 2.1 there is a much more humid climate in the southern parts of the country than in the northern desert and the most optimal system may vary depending on region.

2.6.4 Direct evaporation

There is another cooling method that uses the same principle as desiccant cooling but is much less technically advanced. It is basically a moisturizer and a fan.(Figure 18) The air goes through the machine and is sprayed with water. When the water evaporates it lowers the air temperature and cold air comes into the house. This is a very simple and efficient technique that works well when the relative humidity is low and very poorly when the relative humidity is high. This machine is on the market today in Burkina Faso. Negative about this machine is that it uses water.

Figure 18 - Moisturising cooling machine

3 Method and material

During two months field and laboratory work in Burkina Faso was carried for this report. Experiments on vibrating loam were made in order to acquire physical properties relevant for determining loam as a suitable building material. This chapter describes how the laboratory research was done to produce and examine the specimens

3.1 Material – Loam sample

The soil

Soil was gathered from five different places in Burkina Faso. It was brought to a laboratory for granulometric analysis. The samples were dried at 105°C for four days. An analysis was then made in two steps. First a sieving was performed to identify particles larger than 0,08mm. Then, sedimentation was performed to identify and measure the particles smaller than 0,08mm.

The soil samples from the village Boudry showed a granulometry in accordance with the advice of MINKE (2006 P.65), with a clay content (<0,002mm) of a little over 20% (APPENDIX 4 –). It was chosen as the soil that would be used throughout the entire project.

Figure 19 Soil dried on the floor of the laboratory

Even if all the soil comes from the same place it does not guarantee that the granulometry will be exactly the same. In this case the granulometry can be of great significance for the final results and to minimize the risk of error a precaution was taken. Before the material was used in the project it was sieved and divided into two parts: smaller and larger than 0,08 mm. The granulometry from Boudry (Figure 21) had 48% particles smaller than 0,08mm and 52% larger than the same. For all tests the soil was sieved, divided, measured and mixed according to that percentage. Since the particles smaller than 0,002 mm give the soil much of its strength (MINKE, 2006) it would have been desirable to measure and mix the materials based on that fraction. However that was not possible since the sieving did not register particles smaller than 0,08mm and the sedimentation was done at another laboratory. To simplify the sieving, the soil was put in water 24 hours prior to the sieving. After sieving, the clay was dried at 105°C for four days to remove the chemically bound water. Since the clay dried in lumps it had to be crushed (Figure 20) after drying to secure an even mix. This was done manually with a hammer and a mortar. The larger fraction contains no chemically bound water and was dried on the floor in the laboratory for equal amount of time as the clay (4days, 35-40°C) . (Figure 19)

Figure 20 Crushing of clay

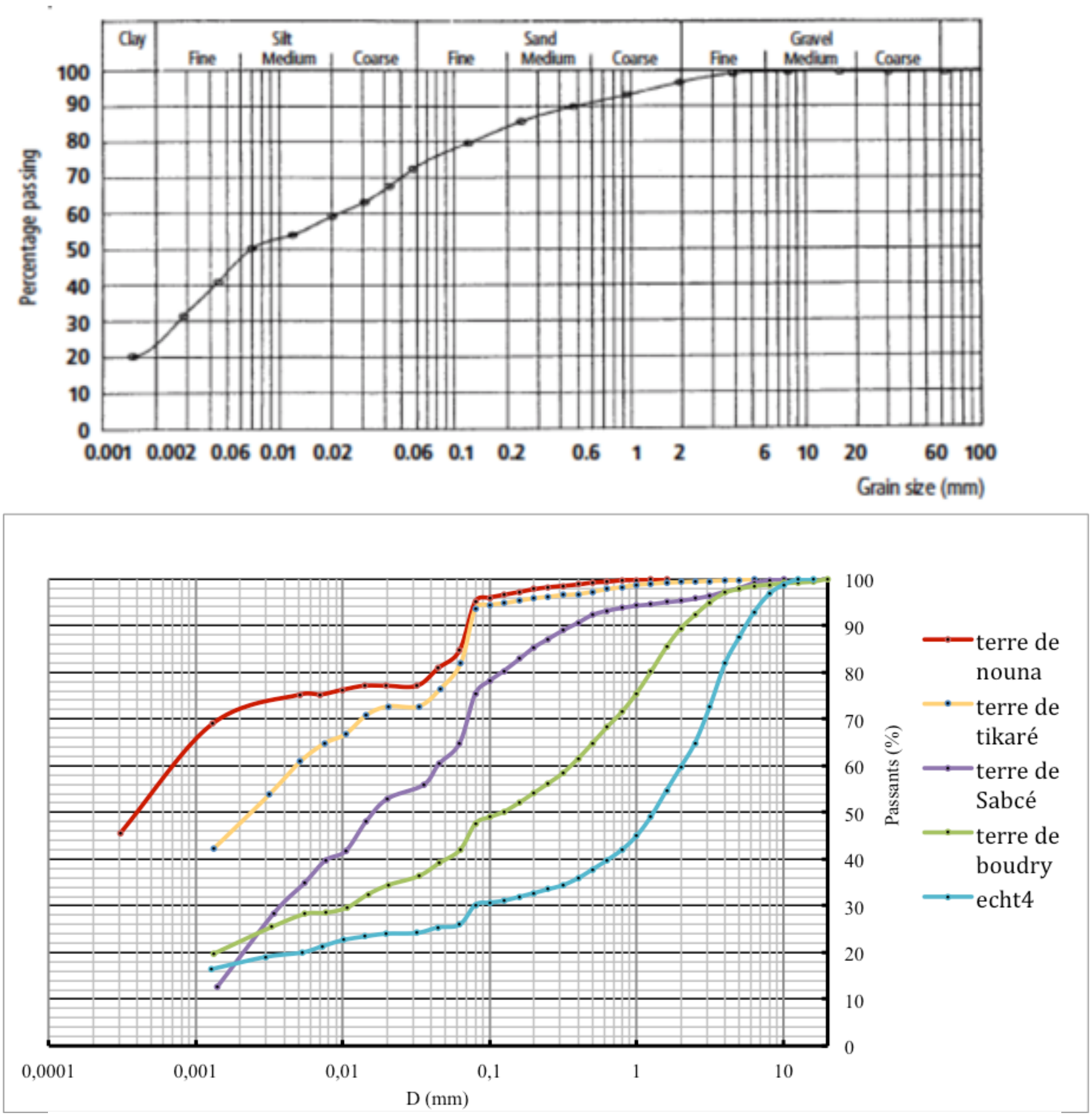


Figure 21 [Top] A good soil granulometry for compressed soil bricks according to MINKE (2006) Parts smaller than 0,002mm have very unique qualities

[Bottom] The green line is the soil from Boudry, which showed desired properties and was used in the experiments

Fiber

Organic fibers were added to some of the samples to see if some of the properties of the bricks could be enhanced. Organic fibers have been added to building material for thousands of years for several purposes. Fiber can lower the lambda-value and reduce shrinkage. It has also been used to improve mechanical strength, something that according to MINKE (2006, P.47) does not apply to cut straw or cut wide fibers. According to MINKE mechanical strength can only be improved using fibers the thickness of human hair.

Two different fibers were, initially, meant to be tested, one more straw-like and one more grass-like. However, due to insufficient equipment and lack of time only the straw fiber was tested. The fiber chosen was from the bissap plant, which is well known in Burkina Faso. Bissap has many uses, for instance it is the main ingredient in a local beverage. The plants were cut and taken to the laboratory. At the laboratory the outer bark was peeled off in order to prevent fungus/mold growth under the bark (Figure 22 The cover of the fibers were peeled off to avoid mold growth.(Figure 22) The material was then dried for two days.

In order to prevent the fibers from absorbing the water added to the mixture the bissap was submerged in water for twenty-four hours prior to use. All the measurements have been made compared to the dry weight of all the materials (except the water). Since the fibers were wet a dry/wet factor hade to be measured. A completely dry test sample of fibers was weighed and then immersed in water for twenty-four hours. The wet material was 4.7 times heavier than the dry fiber, a factor that has been used for all samples.

MINKE (2006 P.48) states that the fiber should be no greater in size than the smallest part of the building element. The smallest element in this test is 4cm but to increase the homogeneity of the mixture the fibers were cut into one cm pieces

Figure 22 The cover of the fibers were peeled off to avoid mold growth

Lime

During the first weeks of this project there were some difficulties to obtain indigenous lime. This resulted in the use of lime from Spain for the first samples. After a month lime from Burkina Faso was procured and was used for most samples. The lime is hydrated lime (non-hydraulic). Three different proportions of lime were tried in the mixture, 0,3%, 1% and 3%.

The domestic lime comes from limestone in Tiara in the southwestern part of Burkina Faso. There the lime was crushed and heated to quicklime. It was then transported to Bobo Dioulasso to be hydrated. (Sourdois, R., 29/4-2013 interview)

Cement

The cement used came from Burkina Faso and is Portland cement following international standard with quality CPA45. 0,3% cement was tried in this project

Water

Since the water eventually evaporates from the mixture it was not considered necessary to test the water quality for this research. Therefore regular tap water was used. Prior to the real experiment, different proportions of water were tried to determine the lowest possible amount of water that could be used and still maintain sufficient workability. If the mixture is too dry it is difficult to produce evenly shaped and flawless bricks. According to MINKE (2006), the lowest possible water quantity is preferred but he also states that the optimum water content is raised when lime is added.

3.2 Making the samples

3.2.1 Mixing and vibrating

First the soil was divided into particles larger or smaller than 0,08mm. Then the parts were weighed and mixed so the quantity was 48% smaller than 0,08 mm and 52% larger. All the other ingredients were weighed and measured.

$$proportion\ of\ additive = u_f = \frac{dry\ weight\ of\ fiber/water/lime/cement}{dry\ weight\ of\ soil\ sample}$$

After weighing, the following procedure was observed:

1. The dry materials were mixed for one minute. If the sample had fibers, they were added after one minute and mixed for another minute. The mixer was an old power drill with a homemade beater (Figure 23) spinning at 125 rpm
2. After that the water was added and stirred with a stick for a few seconds.
3. Then the mixture was rested for one minute so some water could be absorbed by the soil. This was necessary to ensure that the water remained in the mixing bowl instead of splashing out when mixed. Testing showed that it was much easier to mix if the water was allowed to be absorbed for one minute.
4. Then the material was mixed for three minutes
5. After that the mixture was poured into the mold and vibrated for 5 seconds, if the surface was uneven it was gently smoothened with a trowel.
6. Then the mold was put in storage and left to dry.

Figure 23 The materials were mixed with a power drill and then casted in a mold for vibration

3.2.2 Drying

Due to lack of resources and time it was not possible to build a climatic chamber resulting in an inadequately controlled environment. The samples were stored either on a shelf or on the floor (depending on were it was free space) of a naturally ventilated room without air-condition. The room temperature was measured a number of times during different times of the day and it was always between 34-38°C. The relative humidity could unfortunately not be measured due to lack of equipment. (Figure 24)

Figure 24 The samples were protected against rain, wind and sun during drying but the conditions could not completely be controlled

During the first week of drying the samples were covered with a wet bag made of organic fibers. The bag was wetted every day. Using the bag was not planned from the beginning but was a tip from a local builder that explained that in the traditional building they used to cover the newly constructed walls with wet plants or fibers during the hot season to avoid cracks.

3.2.3 The Mold

The tests were conducted with three different types of molds in order to be used for three different tests. (Figure 25)

> *Heat transfer*: A flat rectangular mold with the dimension 330x250x30mm
>
> *Normal stress*: A cylindrical mold with the dimension Ø 100mm and height 116mm, +50mm which was cut off after some drying to reduce surface cracks of the material that was tested.
>
> *Shear stress (Rupture modulus):* Rectangular mold with the dimension 160x40x40mm

At first, metal molds were used to vibrate and dry the samples. It worked poorly because there were gaps in the mold, which led to leaking during the vibration and they were ungainly to assemble and disassemble and the drying was uneven as it only dried upwards. For those reasons one week was spent on building new molds in wood. Because of limited resources and time, it was also decided to only make the rectangular molds in wood (thermal and tensile samples) and continue to use the cylindrical metal mold (compression), as it did not have the same problems with fissures as the other molds. Test #11 and forward are made in the wooden molds.

a)

b)

Figure 25 a) Metal mold for compression

b) Wood mold for thermal measurement

c) Wood mold for tensile measurement

c)

3.2.4 Vibration

As previously said, the material was vibrated instead of compressed, which is normally the case in earth building. There are several reasons to try vibration. One is that it is easy to standardize, all you need is the amplitude and the duration in order to repeat the process. Another is the novelty of it. Very little research has been made on mechanical vibration of soil to make construction material. A third reason is described in Chapter 2.2 – Building with earth, that the lamellar structure of clay particles can, when dynamically moved, organize themselves in a more efficient structure, creating a stronger binding force than would be the case if it were statically compressed. (MINKE, 2006) This experiment investigates how strong the material can be without compression, only vibration

The vibrator is a converted foot massage machine with a frequency of 980 Hertz or almost 59 000Rpm (Rounds per minute). The mold with the sample was put on top of the machine and tied to the vibrating plate so the entire mold moves at a frequency of 980 Hertz (Figure 26) Since vibrating clayey soil to make construction material has never been scientifically documented (as far as the author is aware) it is hard to know how long and at what frequency the most optimal vibration is. A bit of trial and error atempts was conducted and the result was that five seconds seemed good. It was locg enough to make the mixture level in the mold. More than five seconds gave indications of separation in the material.

Figure 26 The vibrator was originally a foot massage machine

3.3 Comparative sample – Cement based mortar

As a comparison to the investigated loam samples, a conventional mortar sample was tested. The sample was made in the same way, and could be compared, as the material used in the modern cement based bricks mentioned in Chapter 2.4.2. The sample was well hydrated. Only the thermal properties were tested on the comparative sample.

3.4 Thermal characterization

Thermal measurements were made to determine the thermo-physical properties of the samples. The properties determined in this report are

- Conductivity (λ)
- Effusivity, (E)
- Diffusivity (a)
- Heat capacity (ρC)

Determination of said properties were made with the Hot Plate Method (Methode du plan chaud) described by JANOT (2006). The method was developed to make accurate thermal measurements with limited means and equipment.

The experiments were conducted at the Laboratoire de Physique et de Chimie de l’Environnement de l’Université de Ouagadougou (LPCE)

Testing of each sample was done at three different occasions: after 14 days of drying, after 28 days of drying and one last test was made when the material was completely acclimatized to the relative humidity of the surrounding air i.e. when the material did not loose weight anymore, due to evaporation of water residues.

3.4.1 Thermal properties - definition

Conductivity - λ

Thermal conductivity is measured as the heat that flows through a material that is one meter thick, when the temperature difference between the two sides of the material is one degree. It is expressed in W/mK and defines how well the material insulate. Low value equals good insulation capacity. If a one-directional flow is assumed, the conductivity can be measured by determining the temperature gradient at the steady state, using Fourier's law. Fourier's law states that the heat flux through a material is proportional to the temperature gradient

$$\boldsymbol{\Phi = \lambda \frac{dT}{dx}} \qquad (1)$$

Φ=Heat flux
dT=Temperature gradient
dx=thickness of the sample

If the current and resistance are known for the heating element the λ-value can be determined using

$$\boldsymbol{\lambda = \frac{RI^2x}{S(T_1 - T_2)}} \qquad (2)$$

R= Recistance of metal heater
I=Intensity of current
x=thickness of sample
S=Surface area of sample
T_1=Temperature on the front surface
T_2=Temperature on the rear surface
The equation applies if the heating plate only heats on one side.

Effusivity – E

Is the speed with which the surface temperature of a material heats up. It is determined by using

$$\boldsymbol{E = \sqrt{\lambda \rho c}} \qquad (3)$$

Diffusivity - α

Is a unit that explains if a material is better at storing or conducting heat. It is directly proportional to the conductivity and inversely proportional to the density and heat capacity.

$$\boldsymbol{\alpha = \frac{\lambda}{\rho c}} \qquad (4)$$

or

$$\alpha = \frac{\lambda^2}{E^2}$$

Heat capacity - c

The heat capacity explains how much heat the material can store and the unit is J/kgK. It is calculated by

$$\boldsymbol{c} = \frac{\boldsymbol{E^2}}{\boldsymbol{\rho\lambda}} \qquad (5)$$

3.4.2 Hot plate method

The experiment was conducted using the Hot Plate Method described by JANNOT (2006). By using a metal plate resistor and temperature sensors (thermometer), the thermal characterization can be established.

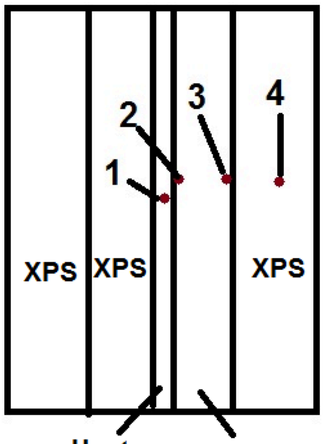
Figure 27 Wood box with heater inide. Coil and resistor

Inside a rectangular box made of wood with the inner dimensions 345x255x150 (slightly bigger than the mold) a heating plate (metal resistor) was placed in the middle. The heating element made of metal was connected to a coil and a rheostat, so all values could be controlled and the temperature could be changed. During an experiment a constant heat flow was applied through the heater and the sample was put next to the heater in order to measure the heat flow thru the sample. In our case we used a 41Ω resistance in the rheostat from a current of 220V with a resistance inside the heating element of 120Ω. (Figure 27) Each test was set at three different current levels i.e. different temperature of the heater. The amperage was set at 0.2, 0.3 and 0.4 Ampere. This was done so a mean value of the result could be calculated to ensure that the results were correct. According to BURSTRÖM (2001) there is usually a higher accuracy the higher temperature difference there is between the heater and the outside air but that is not always true if the sample contains moisture, since then the water evaporation can give inaccurate results. 0.4 Ampere was set as the maximum current because more power could lead to damaging temperatures on the equipment and the samples. Prior to testing, the equipment was checked with a multimeter to make sure the Amperemeter and rheostat were correctly calibrated.

The next step was to put the samples next to the heater. This step can be done in two ways. The most precise is to have two identical samples and put one on each side of the heater. Then, outside of the samples a material with very low lambda-value is used as insulation. In this case XPS (Expanded PolyStyrene) was used with a Lambda-value of 0,034 W/mK. In our case we did not have the possibility to have two identical samples from each test so another method, were only one sample is needed, was used (Figure 28). On one side of the heater there was the sample and then the XPS, on the other side there was only XPS. (Figure 28 c)The length and width of the sample are about ten times the thickness and the XPS was regarded to have a much lower conductivity than the sample. A semi-infinite unidirectional heat flow was assumed in the center of the heater and calculations were made using the equations described in section 3.4.1

a) Heating element, sample and insulation

b) Complete measuring setup



c) Graphical view of setup

Figure 28

There were thermometers inside the heater (1), between the heater and the sample (2), between the sample and the XPS (3) and inside the XPS (4).(Figure 28 c) It was exactly the same procedure for the two versions with one exception. For the one sample version there were naturally only measuring points on the side were the sample is, so four measuring points in total. For the two-sided version there were measuring points on both sides so seven in total, three on each side plus the heater. For the one sided version the calculation formulas are changed so the heat flux is measured to go in one direction instead of two. (JANNOT, 2011 P.68)

Experiments have previously been made using the same equipment with the two-sample method. The accuracy has been around 95% when compared to tests with more advanced equipment. (TOGUYENI, 2013-03-21)

When everything was set and the thermometers are inserted the test was ready to begin. The duration of the tests was 1h35 and the temperature was measured every ten seconds and transferred to an USB-key Figure 28 b)

3.5 Tensile strength

The tensile strength testing was conducted at the state laboratory of Ouagadougou LNBTP (Laboratoire National du Bâtiment et des Travaux Publics). The prismatic samples had a rectangular shape with the dimension 40x40x160 mm (before drying)

The sample was put in a three-point pressure device. Two feet underneath and one active compressing point on top of the material.(Figure 29) The tensile strength was calculated using

$$\boldsymbol{R_t = \frac{3F_t l}{2bh^2}} \qquad (5)$$

R_t=Tensile strength (MPa)
Ff=Force of compression (MN)
l=length between the two feet
b=width of the sample (m)
h=height of the sample
For each sample three specimens were tested so an average could be calculated.
To ensure that the results were correct, a few samples were brought to Sweden and tested at the Ångström laboratory as a comparison to the results from LNBTP

Figure 29 Device for measuring tensile strength

3.6 Compressive strength

The compressive test was conducted on samples of cylindrical shape following standard NF P 18-406. The diameter was 100mm and the height was 116mm.(Figure 30). The strength was calculated using

$$\boldsymbol{R_c = \frac{F_c}{S}} \qquad (6)$$

R_c=Compressive strength (MPa)
F_c=Force of compression (MN)
S=Bottom surface of the sample m^2 $(\frac{\pi Ø^2}{4})$

Figure 30 - Sample to make compression strength test

4 Results - mechanical and thermal experiment

This chapter shows the results from the laboratory experiment of the thermal and mechanical testing.

4.1 Making the samples

4.1.1 Water content

As described in 3.1, different quantities of water was tried to find the optimum water content. When making compressed bricks, water content of 10-15% is common (MINKE, 2006). Experiment showed that for the vibration to work properly, a much looser material composition was needed. A water content of 25 – 40% added water (weight percent) was tried. Different compositions were made to find a mixture with a water content that allowed the vibration to work properly.

The experiments showed that in order to have a sufficient workability of the material, the water content could not be less than 30% for samples without lime and/or cement. For samples with lime and/or cement, the lowest quantity was 35% added water confirming what MINKE (2006 P.46) writes that the optimum water content is raised when lime is added to the mixture. Since high water content easily leads to shrinkage, low water content was desired.

4.1.2 Vibration

Vibration was difficult at the beginning. The metal molds were leaking, making the samples uneven (Figure 31)The vibrating plate was not leveled, something that was adjusted when the wood molds were made.

a)

b)

Figure 31 Metal molds showing the mixture, a) before vibration and b) after vibration

4.2 Drying and cracks

This chapter describes the major problems that occurred with cracks. **Error! Reference source not found.** shows the mixture of all the samples, which kind of mold that was used and if it showed some fissures after drying.

Many of the samples experienced severe cracking during the first days of drying. Especially the samples for the thermal experiment had many and major cracks. The evaporation from the surface seemed to be faster than the speed of capillarity from the inside creating a few micro fissures on the surface. If micro fissures occurred within the first two days it always led to the fissures becoming cracks after further drying (unless fibers were added). After discussion with a traditional builder wet organic bags were put on the samples, which had a positive effect as it slowed down the drying process from the surface. The first 3-4 days the samples were too soft to be moved out of the mold. During those days a lot of corrosion was developed in the metal molds.(Figure 32) After each test the molds had to be polished and the corrosion removed. The thermal molds in steel were leaking during the vibration, making the corners of the sample uneven

Figure 32 Corrosion on the metal molds

Molds of wood

Since it took up to a week before the molds could be reused after each test combined with the other problems it was decided to make molds in wood to see if it could eliminate or decrease some of the problems. The idea was that the wood would allow a drying through all sides creating a more continuous shrinking through the whole material instead of the surface shrinking that occurred with the metal molds where the water only could evaporate through the surface.

With the wooden mold, the process of vibrating was easier and with no leakage, making the mold completely full of material, resulting in a more correct sample. However, there were not enough samples to make any direct assumptions; both the metal mold and the wood mold had samples with and without cracks. It seemed as if the drying was too fast if the wood was dry, something that seemed to create cracks so for test #13 and later, the wooden molds were put in water for five minutes directly prior to vibration. There was only time for one test using this method of wetting the mold but it did not stop the samples from cracking

Fibers

When fibers where added to the mixture, less cracks occurred, both with the metal and wooden mold. Sample #5 with 3% fiber showed less cracking than sample #4 that had 1% fiber. When lime was added the results varied. Sample #8 (0,3% lime, 3%fibers) showed no cracks while sample #11 with the same mixture had almost pervading cracks. On the other hand sample #11 and #12 with 3% fiber, showed much less cracking than sample #13 and #14 which had 1% fiber, regardless if lime was added or not. (Table 1)

Lime and cement

Both lime and cement enhanced the initial drying speed. The surface felt dry after only 1-2 days. For the samples without lime/cement it took at least twice as long. Since the problem with drying the surface too fast existed even before adding lime/cement, it became worse after. When the cement was used it took only a few hours before the cracks started to occur. There was only one sample made with cement but with the samples with lime, the quick surface drying increased with increasing amount of lime making the small fissures presenting themselves faster. For the 0,3% lime (sample #8) it took more than a day for micro fissures to occur but for the 3% lime (sample #7) it took only a few hours.

Table 1 – Visual analysis of samples

Sample*	Water	Lime	Cement	Fiber	Cracks	Usable for further testing	Mold **
# 1 T,C,H	30%	-	-	-	3 major on H, Cracks on all	No, cracks broke the material	M
# 2 T,C,H	35%	-	-	-	Major cracks	No	M
# 3 T,C,H	30%	-	-	-	Major cracks	No	M
# 4 T,C,H	30%	-	-	1 %	Few microfissures on H. Crack on T	H Yes, T No T, one crack through on each	M
# 5 T,C,H	30%	-	-	3%	No	Yes, Shrinkage but no cracks	M
# 6 T,C	30%	1%	-	-	Many after just a few hours	No	M
# 6 H	35%	1%	-	-	Many cracks after just a few hours	No	M
# 7 H1	35%	1%	-	-	Small after a few hours, Big after 1 day	No. cracks through sample	M
# 7 H2	35%	3%	-	-	Small after a few hours, Big after 1 day	No, same as above	M
# 8 H	35%	0,3%	-	3%	No, fine results	Yes	M
# 8 H	30%	-	-	-	Many deep	No	W
# 9 H	35%	-	0,3%	-	Yes, few but deep	No	M
# 10 H	30%	-	-	-	Many, rapid evaporation	No	W
# 11 T	35%	0,3%	-	3%	No, almost none	Yes	W
# 11 T	35%	0,3%	-	3%	No almost none	Yes	W
# 12 T	30%	-	-	3%	No almost none	Yes	W
# 12 T	30%	-	-	3%	No almost none	Yes	W
#11 H	35%	0,3%	-	3%	Yes, two almost through	Maybe	W
#11 H	35%	0,3%	-	3%	One big Through	No	W
#12 H	30%	-	-	3%	Few, small	Probably	W
#12 C	35%	0,3%	-	3%	No	Yes	M
#13 T	30%	-	-	1%	Yes, one in each in 4 of 6	No	W
#13 T	30%	-	-	1%	Yes, one in each in 3 of 6	No	W
#14 T	35%	0,3%	-	1%	Yes, one in each in 3 of 6	Maybe	W
#14 T	35%	0,3%	-	1%	Yes, one in each in 3 of 6	Maybe	W
#13 H	30%	-	-	1%	Yes, many deep	No	W
#14 H	35%	0,3%	-	1%	Yes, many deep	No	W

*T=Tensile, C=Compression, H=Thermal (Heat)

4.3 Shrinkage and density

Shrinkage

Because of the problem with the fissures previously mentioned, only samples #8, #11 and#12 could be weighed and measured. They were weighed and measured directly after the vibration and then again after 14 days of drying. The results are presented in Table 2. The samples with 35% water, 3% fiber and 0,3% Lime had an average shrinking of 22% while the samples with 30% water 3% fiber and no lime had a slightly lower shrinkage of 19%.

Density

The average density of the samples with 35% Water, 3% fiber and 0,3% lime were 1556 kg/m^3. The average density for the sample with30% water, 3% fiber and no lime was 1559 kg/m^3

Some irregularities appear when comparing the density of similar samples (Table 2). It could be because many of the samples were small with a total weight of 300 gram and the scale had a precision of ±25 gram.

Table 2 Density of samples before and after drying

	At cast			After 14 days of drying			
Sample# W=Water F=Fiber L=Lime	Weight (kg)	Volume (cm^3)	Density (kg/m^3)	Weight (kg)	Volume (cm^3)	Density (kg/m^3)	Shrinkage (%)
8. W35% F3% L0,3%	4,50	2490	1,8 x 10^3	3,3	1886	1,8 x 10^3	24,3
11.W35% F3% L0,3%	4,10	2490	1,6 x 10^3	3,0	1878	1,6 x 10^3	24,6
11.W35% F3% L0,3%	4,10	2490	1,6 x 10^3	3,1	1900	1,6 x 10^3	23,7
11,1.W35% F3% L0,3%	0,43	256	1,7 x 10^3	0,3	202	1,5 x 10^3	21,0
11,2.W35% F3% L0,3%	0,43	256	1,7 x 10^3	0,3	212	1,4 x 10^3	17,1
11,3.W35% F3% L0,3%	0,43	256	1,7 x 10^3	0,3	205	1,5 x 10^3	19,8
12.W30% F3%	4,35	2490	1,7 x 10^3	3,3	2059	1,6 x 10^3	17,3
12,1.W30% F3%	0,48	256	1,9 x 10^3	0,3	194	1,5 x 10^3	24,1
12,2W30% F3%	0,48	256	1,9 x 10^3	0,35	214	1,6 x 10^3	16,5
12,3W30% F3%	0,48	256	1,9 x 10^3	0,3	207	1,5 x 10^3	19,3

4.4 Thermal properties

Beacuse of the fissures only three samples could be used for the thermal experiment.

- #8 - 35% water, 3% fiber, 0,3% lime
- #12 – 30% water 3% fiber
- Cement brick (see 3.3)

The results from the experiments described in 3.4 are shown in Table 3

Table 3 Results from the thermal test

Mixture	Density Kg.m^{-3}	Power W	Effusivity KJ.m^{-2}.°C^{-1}.s$^{-1/2}$	Δ Temp °C	λ W/mK	Heat capacity J.kg^{-1}.°C^{-1}	Diffusivity mm^2/s
35%Water		4,8	0,7	0,4	4,3	0,1 x 10^3	39,6
3% Fiber	1750	10,8	2,0	1,4	2,8	0,8 x 10^3	1,9
0,3% Lime		19,2	1,7	7,5	0,9	1,9 x 10^3	0,3
30%Water		4,8	0,8	6,4	0,3	1,5 x 10^3	0,1
3% Fiber	1603	10,8	1,7	2,0	1,9	0,9 x 10^3	1,3
		19,2	1,8	3,4	2,0	1,0 x 10^3	1,2
Cement		4,8	1,4	1,1	1,5	0,7 x 10^3	1,1
brick	1956	10,8	1,9	1,2	3,0	0,6 x 10^3	2,6 x 10^{-6}
		19,2	1,6	5,2	1,2	1,1 x 10^3	5,57 x 10^{-07}

Irregularities and discrepancies

The results were irregular and there is a discrepancy between the gained results and what is theoretically plausible. The conductivity is significantly lowered with increasing current. As described by BURSTRÖM (2001) some irregularity could possibly be expected due to water evaporation in the sample but those irregularities should be much lower than this.

According to MINKE (2006, P.36) there is an almost linear relationship between the conductivity and the density of loam as building element. Low density has low conductivity and vice versa. Our samples have a density of a little over 1500 kg/m^3, which should give a λ-value of between 0,6-0,8 W/mK

Probable cause to the discrepancy

The high temperature in the laboratory (over 35°C) made the stationary difference between the heater and the outside air limited. This in turn made the difference in one test between both sides of the sample so low that for the 0,2 A test, the difference did not even exceed 1 degree which is the minimum allowed difference when using this method (JANNOT 2011). Another reason for the small difference can be explained by the sample having an uneven surface. During drying the sample bent making it a little convex. When the sample was put next to the heater there were a few millimeters of air between heater and sample. For the analytical calculations that was corrected by raising the Rc (APPENDIX 5 – HOT PLATE METHOD) but for the experimental value the convection from the air void could perhaps cause enough disturbance not to get a good read from the thermal measuring points. None of the results can be used with certainty since the irregularities were too significant.

4.5 Mechanical properties

4.5.1 Tensile strength – Laboratory in University of Ouagadougo

Only two tensile samples passed the problems with fissures mentioned in 4.2 and could be used for further experiment. Sample #11 with 35% water, 3% fiber and 0,3% lime and #12 with 30% water, 3% fiber. Three specimens of each sample were tested. One manual machine was used for the first specimen but when the machine had reached its limit at 20,4 kN, the specimen had still not cracked. Therefore another machine was used for the other five specimens. Before conducting the experiment with the loam sample, a sample with known mechanical characteristics made of unreinforced concrete were tried in both machines to make sure it was correctly functional. The trial run did not indicate any problems with the machine. Despite that the results presented in Table 4 shows extremely high tensile strength on all specimens.
According to MINKE, 2006 loam samples have previously showed results of between 0,16MPa for clay with low cohesion (kaolinite) and up to 22MPa for samples with a high content of montmorillonite, suggesting that the values obtained in our experiments are not correct. Our results were almost ten times higher than the best results that MINKE obtained.

Table 4 Results from the tensile test

Mixture	Force kN	Resistance N/mm^2	Mean value N/mm^2
35%Water, 3% Fiber 0,3% Lime	67,2	181,17	175,11
35%Water, 3% Fiber 0,3% Lime	53,6	144,74	
35%Water, 3% Fiber 0,3% Lime	67,3	199,41	
30%Water, 3% Fiber	20,4	58,20*	---
30%Water, 3% Fiber	66,5	191,63	162,08
30%Water, 3% Fiber	46,6	132,52	

**First test was conducted with a machine that reached its limit and is not useable. A more powerful machine was used for the other specimens.*

Probable cause of the high values.
Since a successful trial test was conducted prior to the experiment, it is not likely that the machine was broken. The machines however did not have a recording option so it was not possible to obtain the tensile curve. The machine is usually used for unreinforced concrete. Concrete is a material that has a brittle breakage (BURSTRÖM, 2001, P.108) meaning that the breakage occurs at the same time as the first

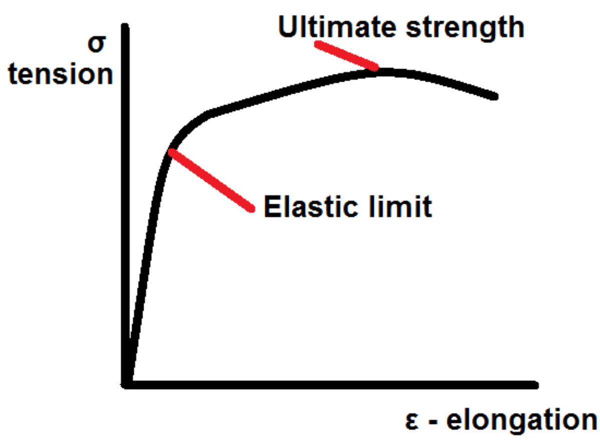


Figure 33 Tension-Elongation curve

deformation. The machine is therefore calibrated to stop when the material breaks (Ultimate strength). The loam samples have a different binding force than concrete and they are reinforced with fibers. That means that the deformation could go on for a long time before the material completely breaks and the interesting value is not when it breaks but when plastic deformations start to occur (elastic limit). (Figure 33). The high results probably comes from a completely wrong sensitivity calibrated in the machine.

4.5.2 Tensile strength – Laboratory in Uppsala University

As mentioned in section 3.5, 4 samples were brought to the Ångström Laboratory at Uppsala University, Sweden, for additional testing. The force and deformation was registered hundred times per second. Two specimen with 3% fibre and 0,3% lime and two specimens with 3%fibre and no lime were tested. To avoid local destruction on the samples from the pressuring pins, two 5 mm thicks rubber pieces were used, one on top of the sample and one underneath (Figure 34). The results registered here were more likely to be correct than the previous results obtained in Burkina Faso. The two samples were similar with an elastic limit just below 1 MPa. Results are shown in APPENDIX 6.

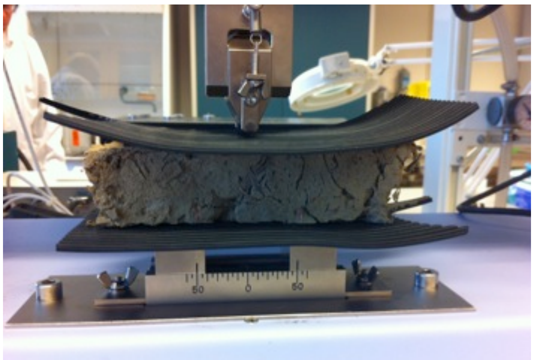


Figure 34 Tensile strenth testing machine in Uppsala, Seden

5 DISCUSSION

The modern building culture of West Africa today leads to one of two things: expensive air-conditioning for those who can afford it or uncomfortable living conditions for those who can not. An energy efficient building system made of local materials would most certainly have a great positive impact on people's living standard as well as their wallets, not to mention the environment. The unstable and overloaded power grid of Burkina Faso would get some breathing room and the import of expensive energy would decrease.

During the work of this report there were some setbacks. Especially when it came to the laboratory experiments. Many of the results were either too irregular or were simply not realistic. There were several reasons for that. Partially it was because we tried to find a new approach to building with soil. Clay has many interesting qualities and especially how it needs dynamic movement to gain the most optimal binding force. The vibration could very well be a good way to create that dynamics. Unfortunately the vibration comes with some problems. Some of the problems were solved during the work of this report but for some problems there was no time to completely understand and find a solution. The main problem to solve is the problem with high water content leading to cracks and shrinkage. The high water content was also the reason why the samples had to be kept in the molds for several days making it impossible to produce more samples. The cracks seemed impossible to avoid and the extreme heat during the drying period did not help. In order to continue using vibration, something has to be done about that problem.

Even if the problems with cracks could be solved, there is still the problem with high water content leading to a shrinkage of about 20%. Such severe shrinkage would definitely create problems if a monolithic construction were made. Even for adobe bricks this is a problem because the shrinkage is not exact so the bricks would not be of exactly the same size making them hard to standardize.

One way to decrease the water content could be to combine vibration with compression. The compression helps filling out the voids that can occur as a side effect of lower water content, and the vibration helps to organize the particles in the strongest possible way. Dynamic movement has been scientifically proven to increase the binding force of building elements of clay soil and so has compression.

Instead of making bricks, one could learn from the Kasena houses in the southeast of Burkina Faso. Monolithic houses are more resistant against surface degradation from sun, wind and rain, than houses made of bricks. Building rammed earth houses would also eliminate the problem with molds that cannot be used for several days because of the long drying process.

Using fibers can significantly improve the insulation of loam as construction element but not enough to build a passive house. The walls would simply be too thick. The setbacks with the experiments is that it is impossible to exclude or include clay as a load-bearing element but visits to constructions sites, both modern and historical, shows that it can bear loads.

As all materials with high density it has a high thermal storage capacity. In order to build a passive house, some kind of low conductivity material has to be in the walls and the roof. Organic fibers have proven to work well in Swedish conditions and can be studied as an alternative in Burkina Faso since it is an environmentally friendly and renewable source. However, there are a few factors to take into consideration when building with organic materials. The termites are a major problem and like always when building well-insulated elements, moisture is a risk factor.

Using soil has many positive aspects. It exists basically everywhere and therefore it can be a local material wherever the construction site is. That reduces the expensive transportation cost and lowers the environmental pollution. It is labor-intensive work, which complies well with the fact that the labor cost in Burkina Faso is low. If a simple production technique is developed, it even allows for the poor people to live in dwellings with a nice indoor climate.

Clay consists of different minerals and it is important to study the soil for each construction. If the clay contains a large quantity of the smallest minerals (montmorillonite) it has a stronger cohesive effect than if the clay contained more Kaolinite. The fact that the soil is different depending on location makes it a challenge to develop a rational building system.

Unfired clay has certain sensitivity against water. This is something that has to be taken into careful consideration when designing a building. Previous attempts to build modern houses with soil show the importance of doing proper research before building. The Pan African Institute for Development is the most visual example of unfortunate construction materials and methods. No capillary-breaking layer was put in the foundation, making it easy for water to be absorbed from the ground into the walls. The cement binder used for the joints and plaster worked poorly together with the compressed earth bricks.

For the thermal test, it would probably have been more accurate to use a cooling medium around the measured material but that was not possible with available resources. Previous research shows that it is much more accurate to use one sample on each side of the heater when using the hot-plate method instead of on only one side.

The conditions when the experiments were conducted were extremely hot. Temperatures over 40°C were not uncommon. When using the hot plate method it is important to get a high enough temperature difference between the thermocouples on each side of the sample. A heat flux of $66W/m^2$ is not sufficient when the ambient air is too warm.

The energy situation is not the best in Burkina Faso and the expensive import of electricity makes it reasonable to find other solutions to cooling than compressor driven air-conditioning. Earth cooling is an alternative worth considering but more measurements of the ground temperature needs to be done.

6 Continuing research

This report and the work that has led to it is only the beginning of the development of an environmentally friendly building system. Much is still left to be done before this concept can be a reality. There are a few areas that is especially important to do further research on, some can be done in Sweden and some are better done in field:

6.1 The structure

6.1.1 Further studies on soil as a building element

Lowering water content

More research has to be done on the soil. The high water content that was needed for sufficient workability during vibration led to many problems so one important step is to find a way to lower the water content. The vibration in combination with compression mentioned before could be a solution. Adding more lime, or maybe add some hydraulic lime, into the mixture could be another.

Joints

If bricks are used it is important to do further research on the composition of the material in the joints. As shown in this report there have been problems, in previous attempts of earth building, with joints not attaching properly to the bricks. A mortar with adequate properties needs to be developed.

Monolithic walls

Monolithic structures are proven stronger than structures of bricks and are therefore an interesting alternative, especially since buildings made of loam have a tendency to be sensitive to penetrating water. More practical research should be conducted in developing a rational and fast method of building monolithic walls with loam.

Pierre Taillé stones

Laboratory experiments on the soft red stone called Pierre Taillé should be made to determine the thermal and mechanical properties of the stone.

6.1.2 Insulation

Even when fibers are added to the loam, the heat conductivity is too high for it to work as the only insulation material. The clay elements would probably work best as heat storage. Some kind of insulation needs to be added.

Organic insulation

Organic insulation is a good alternative to analyze. It is renewable, can almost always be found locally and has low conductivity. If residues, for example from the rice crops, can be used there is another benefit. Organic fibers do, however, have some negative side effects. It needs to be treated to be resistant against fire, mold and insects. A big problem in Burkina Faso is the termites. Research has to be made on how to make the organic material resistant against these problems. Research results from Sweden on insulation of cellulose can be of assistance.

If organic insulation is used it is also important to do simulations of the relative humidity in the walls so no unexpected problems occur.

Hempcrete
Hempcrete is a mixture of hemp, lime and sometimes cement. It has low conductivity (0,07-0,09) and is according to manufacturers both fire retardant and has a natural protection against molds and insect due to its alkaline properties. It can be built as bricks or casted with formwork. The material is relatively new but the production is at the moment mainly in southern Europe. It is an interesting material worth investigating further and the transition from todays building culture could be smooth due to similar production techniques. The hemp is a fast growing plant that can thrive in many different conditions and usually needs no help from pesticide or fertilizer to survive.

6.1.3 Roof
Both the structural and the insulating parts of the roof need to be developed. For the insulation, the organic fibers is an alternative, another alternative could be to make longer elements of Hempcrete. Maybe those elements could even replace the load-bearing structure.

For the load bearing structure there are presently two alternatives; wood and steel beams. The steel beams are expensive and need a lot of energy in production. The wood beams have problems when low quality wood is used. It changes volume with changing moisture content, creating cracks between roof and wall. It is also sensitive to termites.

The roof cover is usually made of corrugated metal plates. Research should be made to find possible alternatives. A construction that would probably be too expensive but still worth looking into is to cover the roof with photovoltaic and solar thermal collectors. If it can cover the whole roof, no other cover is needed and a financial saving can be made, covering part of the expenses for the photovoltaic. Financial, technical and practical investigations should be carried out on this subject.

6.2 Ventilation

6.2.1 Solar chimney
A solar chimney should be simulated and built to measure the airflow. Those measurements could then be used to create dimensioning software as assistance for the engineers and architects designing the house.

6.2.2 Earth cooling

More measurements of the ground in Burkina Faso should be made to form a base for analysis and to determine optimal depth of the ventilation pipes. Calculations and simulations based on those measurements should be made to form a dimensioning tool as assistance for the engineers and architects designing the house.

6.2.3 Heat driven or electrical cooling

Burkina Faso has a relative humidity varying between 15% and 100% (APPENDIX 1 – CLIMATE DATA) Research should be done on whether desiccant and/or absorption cooling can be a functional alternative in the climate of Burkina Faso. Absorption cooling works best when the latent cooling load is low and the desiccant cooling works better when the latent cooling load is high (RYDSTRAND et al, 2004). At least in the southern part of Burkina Faso it can be assumed that the latent cooling load is high but this issue needs further research. Both methods are heat driven and a comparative study should be made to see which one is more suitable in Burkina Faso in combination with solar collectors. A comparison should also be made between the heat driven systems and a system, using photovoltaic and a compressor driven air-conditioning. The most important question in the end will be: Which system is financially most profitable?

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1. APPENDIX 1 – CLIMATE DATA

Meteorogical data of Ouagadougou town

(mean value from 1992 to 2006) : 14 years

Month	Air velocity (m/s)	Static pressure (10^2 Pa)	$\bar{T}_{max}$ (°C)	$\bar{T}_{min}$ (°C)	$\bar{T}$ (°C)	RH_{max} (%)	RH_{min} (%)	$\bar{G}_h$ ($MJ.m^{-2}$ day^{-1})
January	2.55	977.15	33.43	18.37	25.9	40.33	14.67	15.94
February	2.65	975.80	36.70	21.67	29.185	40.00	14.00	17.94
March	2.45	974.85	39.27	24.87	32.07	40.33	13.67	18.71
April	2.50	973.65	39.93	27.33	33.63	57.67	23.00	18.60
May	2.95	975.15	38.07	27.13	32.6	73.00	33.00	18.97
June	2.95	977.25	35.80	25.37	30.585	82.00	41.33	18.52
July	2.25	977.65	32.47	23.33	27.9	91.00	53.67	17.09
August	1.95	977.75	31.53	23.03	27.28	94.00	59.33	15.68
September	1.95	977.05	32.77	23.23	28	92.33	54.67	17.38
October	1.80	976.20	36.23	23.87	30.05	82.67	36.00	17.84
November	1.50	975.90	36.17	20.07	28.12	63.67	19.00	16.89
December	1.70	975.85	34.70	17.97	26.335	52.00	15.67	15.84

$\bar{T}_{max}$ = maximum temperature (mean value of 14 years)
$\bar{T}_{min}$ = minimum temperature (mean value of 14 years)
$\bar{T}$ = mean temperature
RH_{max} Maximum relative humidity (hygrometry)
RH_{min} : minimum relative humidity
$\bar{G}_h$: mean daily global irradiation

Mean value over the whole year (1992-2006) = $\sum T, i \quad = 29{,}3^0$C

2. APPENDIX 2 – MODERN BUILDING

There is a procedure on how to build according to construction permits but many times people can not afford all the security measurments so they disregard or replace certain elements with cheaper ones. The following description is from a building that is in its end phase of being constructed today in Ouagadougou, following the recommended guidelines.

First the government or city counsil (after 2006) decides that an area is fitted for residential building. They then tell the owners of the land that they can either build a house for themself on the property or if they do not want to or can not afford it they can sell the land to someone else that can build on it. The important thing is that a dwelling is being built on the property. This is a measurement taken from the government to meet the increasing residential demand that comes from the rapidly growing population in the capital

When all the papers for the property ownership are finished, the government requires a geotechnical survey of the soil and mechanical strength calculations of the building and a fire safety plan. No requirement on energy calculations or requirements on insulation are needed (DISSA, 2013)

When the building permit has been officially signed it is ok to start building. The first thing usually being made is a 2-meter high wall around the entire property to enclose the yard. The foundation work commences when the permit is approved.

Foundation

This is sort of a mix of slab and plinth-course foundation

-First, the top layer of soil is removed because it is usually of bad quality.

-You then dig a 0,3x0,3 m ditch were all the walls will be. Excavators are an unusual sight on construction sites in Burkina Faso and for a family house all the foundation work is done by hand.

-When the ditch is done you dig additional 1x1x1m pits were all the pillars that bear loads from the second floor will be

Foundation work

-Put 10cm concrete directly in the ditch (but not the big pits)
- Put another 10cm of concrete in the ditch but leave space for all the pillars.
-Now put Concrete in all the pits to make feet for the pillars, with reinforcement for both the feet (horizontal) and the pillars (vertical).
-Build two layers of solid cement/sand based bricks. Continue to make the concrete pillars successively as the walls are rising using the walls as the mold for the concrete.
-On top of the two layers of bricks, make a ”chaînage” of 20 cm concrete
-Inside every ”room” the floor is now 30cm lower than the wall foundation. To fill that difference, a very strong soil called terre rouge is being used. It is applied in three layers with watering and packing between each layer.
- The reason for all the steps is that it is important to reach good soil to base the foundation. The reason that the foundation is raised so high is that when the main road is being renovated a layer of gravel is put on the road. The road is not strong, especially not against heavy trucks during rain season. Regular maintenance is necessary and in practice it means adding gravel to even holes and bumps and the level of the road can increase significantly during a few decades. If the road gets higher than the floor level there is great risk of flooding during the rainy season. A precaution is therefore taken by elevating the floor level to avoid future unpleasanties.
-Small ditches are now made in the gravel to lie out the pipework
-5 cm of sand is put on the room surface to even out to the same level as the wall foundation. The sand also works as drainage and reduces capillarity suction.
-To stop the moisture from coming up to the slab altogether, a plastic foil is laid out on all the wall surfaces. It is not however laid out on the wall foundation, leaving an unwanted transportation route for moisture passage.
- Then a mesh of reinforcement is being laid out, on which the electrical wires are being attached to.
-It is now time for perfusing the 10 cm thick concrete slab.


Hollow bricks and concrete pillars

Walls

The walls are being built with a hollow, unreinforced brick made of cement and sand. The bricks can have small varieties in appearance but they usually have the dimension 400x195x150 and the interior consist of two to three holes. The top of the brick is solid and the bricks

are therefore not completely hollow.
The bricks are being masoned with joints of similar mortar as the bricks. After the masonry is finished, the wall gets a cement-based plaster cover on both sides.

The bricks are not considered to be load bearing and the concrete pillars going through the foundation are continuously being casted up to the second floor or the roof to take care of the loads.

The windows and doors are usually not so big. The low budget one is the same window blind of metal without glass that is being used in the modern clay buildings. They are small and do not let in much light. The more expensive version has a similarity to European windows, especially in southern Europe. It is a single glazed window with a frame of aluminum. The glazing is sometimes covered with a sunscreen layer to prevent the heat from coming in. The cover is so obscure that it darkens the window to the extent that artificial lighting is often needed even during daytime.

Roof
Almost all roofs in Ouagadougou are made of corrugated metal sheets. Usually it is a slightly sloped shed roof and the beams are often made of wood, but in more expensive buildings steel beams and rafters are being used. The dimension of the construction is usually very lean since no snow loads are taken into consideration based on the fact that it never snows.
Many times it is impossible to see the roofs from the outside because the outer walls continue 30-50 cm above the roof. If you can afford it you also build a ceiling of, for example, homemade plasterboard but many people just have the metal roof on the inside.

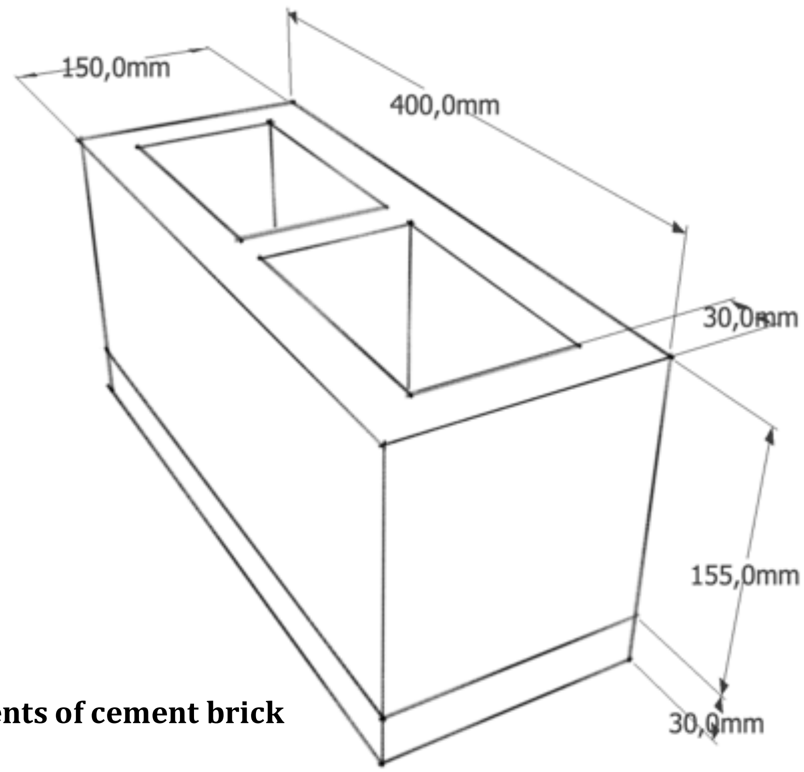
There is a small resistance against using wood in the roof structure. One reason is that termites can eat it. The other reason is the shifting humidity that makes the wood move causing cracks were it is attached to the wall. These cracks can get so big that you'll get unwanted airflow bringing in dust from the outside.

The recommended height of a level is 3m of open air so the warmest air can stay above the person's heads. This is one place were many people save in on their expenses by lowering the ceiling/roof level to about 2.40 m. That means the warm air will get much closer to the persons in the building

3. APPENDIX 3 – U-VALUE CEMENT BRICK

The heat can be transferred in three ways. Convection, Radiation and Conductivity but the term *heat conductivity* usually refers to a combination of all of the above mentioned. This is because it is, in practice, very hard to differentiate between the different energy mechanisms. Especially in construction parts, who are often combined of different materials. (BURSTRÖM, 2001)

When calculating the λ-value of a hollow brick, all of those aspects must be taken into consideration. In this report that has been done in accordance with ISO 6946:1996 and ISO 6946 :2007 . The calculation method and actual calculations can be seen below. Since the results from the experiments were inconclusive, values from previous research had to be found. According to BURSTRÖM a cement/sand based mortar has a heat conductivity of 1W/mK. For a brick with two voids dimensions it gives a total heat conductivity, including joints, of **0,822 W/mK**. The air temperature is set at 36°C on the outside of the void and 27°C on the inside.



Measurements of cement brick

The resistance (R) is calculated as

$$\boldsymbol{R} = \frac{d}{\lambda} \; (m^2K/W) \qquad \textbf{Equation 1}$$

d=thickness of material (m)
λ=heat conductivity (W/mK)

For the brick the R-value is R_{brick}0,183 m^{2}K/W. 1 cm thick plaster is applied to each side of the brick. The plaster has the same conductivity as the mortar so that $R_{plaster} = 0{,}02$ m^{2}K/W

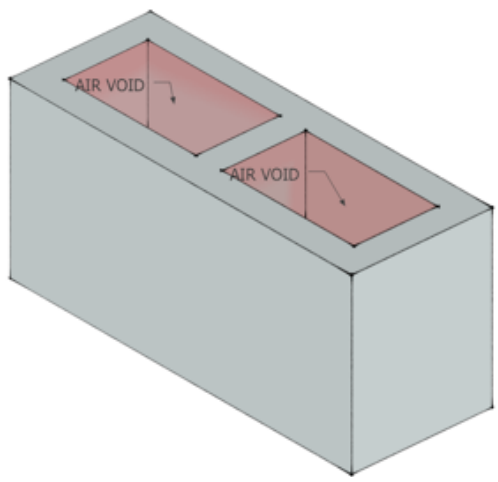
R_{tot} can then be calculated. Since it is a wall, the still air on the outside and inside of the wall surface (R_{si} and R_{se}) can be considered to be 0,13 and 0,04 (Sandin, 2010)

$R_{tot} = 0{,}373$ m^{2}K/W

The U-value is a popular value to use when defining and comparing the thermal properties of a construction element. It is the defined as the energy required to maintain a temperature on a surface of 1m^2 when the temperature difference between both sides of the element is 1°C. It is the inverted value of R_{tot}
$\boldsymbol{U_{tot}} = \mathbf{2,681}$ W/m^{2}K

Calculating voided masonry should be done in two steps. (Anderson, B, 2006 p.8)
According to the standard EN ISO 6946, the first step is calculating the thermal resistance with the *Combined Method*. The surface resistance is now considered to be zero. The second step is to use that result and calculate the u-value with the brick as a homogenous unit. Step two also allows for calculation of mortar joints (Anderson, B, 2006 p.8) To get a better overview of what is actually calculated, the two steps have been divided into five smaller steps. It still follows ISO 6946 but with a better control of every step:

#1.Calculate the air void



ISO 6946 (p.17) requires the air void to be calculated as follows:

$$R_g = \frac{1}{h_a + h_r}$$

where
R_g = thermal resistance of airspace
h_a = conduction/convection coefficient
h_r = radiative coefficient

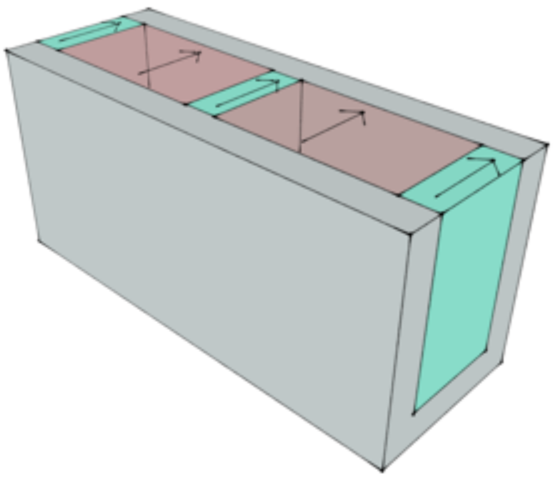
$$h_r = \frac{h_{r0}}{\frac{1}{\epsilon_1} + \frac{1}{\epsilon_2} - 2 + \frac{2}{1 + \sqrt{1 + \frac{d^2}{b^2}} - \frac{d}{b}}}$$

where
d= thickness of the airspace (following the heat flow)
b= width of the airspace
ϵ_1, ϵ_2= hemispherical emissivities of the surface on the warm and cold faces of the airspace. Is normally set to 0,9 (iso 6946-2007 p.12)
$h_{a\text{wall}}$ is the largest of 1,95 or $1,14 * (\Delta T)^{\frac{1}{3}}$ (Use the latter if $\Delta T > 5^0$C)
ΔT = Difference in temperature between the cold and the warm side of the air void
h_{r0} = Black body radiative coefficient *see table below*
$h_{r0} = 4\sigma T_m^3$
$\sigma = Stefan\ Boltzmann\ constant$ $5,67 * 10^{-8}$W/m^{2}K^4
$\bar{T}$ = mean thermodynamic temperature of the surface and of its surroundings, in K

Mean temperature ^{0}C	h_{r0} W/(m^{2}K)
-10	4,1
0	4,6
10	5,1
20	5,7
30	6,3

Mean value of Burkina Faso are 29,3^{0}C. h_{r0} is approximately set to 6.3

#2.Use parallel method to calculate #1/concrete



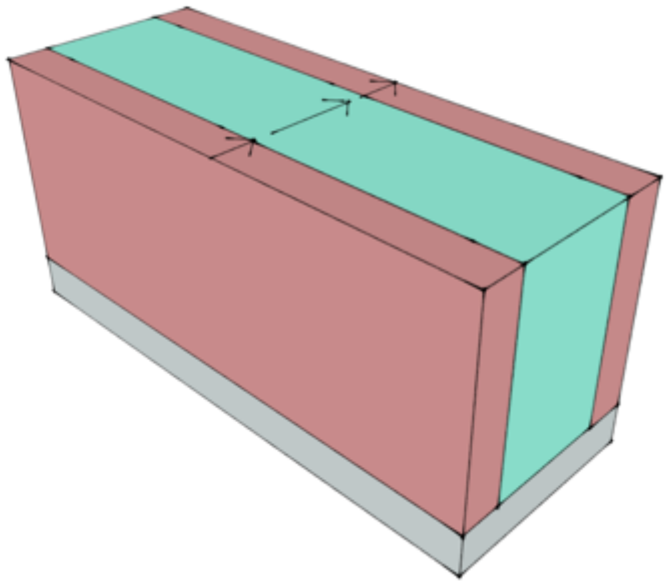
The previously described *Combined Method* consists of two different ways of calculating λ-value in inhomogenous walls. The parallel-method gives the maximum value of λ and the serial method gives the minimum value of λ. The truth always lays somewhere in between. (BURSTRÖM, 2001) However, because of the big difference in λ-value between the air void and the concrete, the author believes that the most accurate result will be to first use the parallel-method (2) within the air void and and calculate an average λ-value of the air and the concrete and then use the serial-method to calculate the average for the whole brick (3) This will give a worse result than reality in the first calculation and a better result in the second.

$\lambda_p = V_1\lambda_1 + V_2\lambda_2$

where

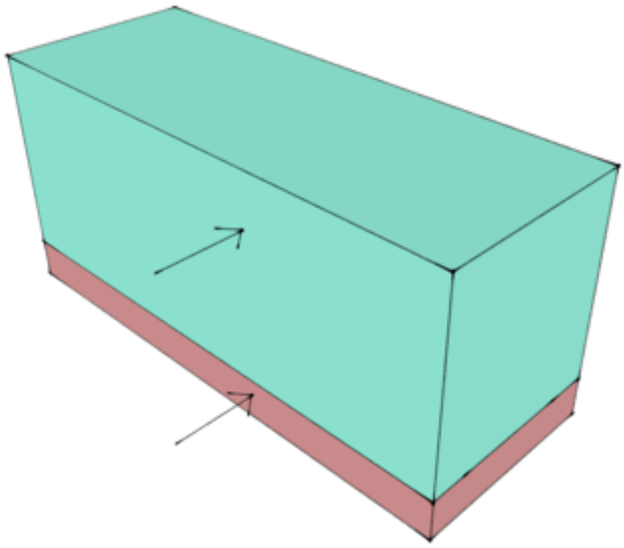
V=percentage of area

#3.Calculating serial method with concrete-#2-concrete



Heat conductivity calculation with serial method
$\lambda_s^{-1} = \lambda_1^{-1}V_1 + \lambda_2^{-1}V_2$ (BURSTRÖM, 2001)

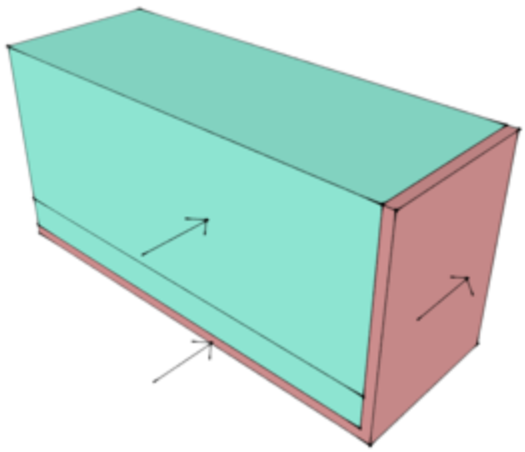
#4 Calculate bottom/mortar joint/-#3 with both methods



When the two calculated materials have fairly similar λ-value, the λ-value usually lies somewhere in the middle (BURSTRÖM, 2001) and it is recommended to use the mean value of the parallell and serial method (ISO 6946:2007, p8)

$\lambda = \frac{\lambda_p + \lambda_s}{2}$ (ISO 6946:2007, p8)

#5 Calculate mortar joint and -#4 with mean value of parallell and lambda-value



Mortar joints can in normal cases of masonry be disregarded if the brick has a thermal conductivity greater than 0,5W/m*K. This is however not the case when the thickness of the building block >105mm. In normal (dense) masonry units, it is therefore allowed to disregard joints. (Anderson, B, 2006 p.7)

In this case, the block element has a thickness of 150mm and must be calculated with the volume percentage of joint in accordance to following formula: (Anderson, B, 2006 p.7)

$$1 - \frac{\text{block length* block height}}{(\text{block length} + \text{joint thickness})(\text{block height} + \text{joint thickness*})} + 0{,}001$$

where the term 0,001 represents a correction term for half blocks at corners.

The final step is to summarize and calculate the equations in the correct order

λ-value calculation						
ISO 6946	**Type** Mortar brick	**Project** Burkina Faso 2013				
Brick properties						
	Brick size	**Thickness of concrete**	**Nr of voids**	**Total concrete**	**Air void**	**Total Air Void**
Width [mm]	400	30	2	90	155	310
Height [mm]	185	30	1	30	155	155
Depth [mm]	150	30	1	60	90	90
Joint side [mm]	10	λ_joint [W/mK]	1,000	T_ute	36,0	
Joint bottom [mm]	10	λ_concrete [W/mK]	1,000	T_inne	27,0	
Step 1	Calculate air void					
h_a,wall	1,949					
ΔT C	5,0					
d [m]	0,090					
b [m]	0,155					
ε_1	0,900					
ε_2	0,900					
h_r,o [W/m ^2K]	6,413					
T_m	31,500					
T_ute	36,000					
T_inne	27,000					
h_r	4,300					
R_g	0,160					
λ_air [W/mK]	0,562					

Step 2	Calculate step 1 + concrete	Parallell method
V_concrete	0,225	
V_air	0,775	
V_tot	0,400	
λ_air [W/mK]	0,562	
λ_concrete [W/mK]	1,000	
λ_p2[W/mK]	0,661	
Step 3	Calculating concrete-step 2-concret	Serial method
d_concrete	0,400	
d_2	0,600	
d_tot	0,150	
λ_concrete [W/mK]	1,000	
λ_p2 [W/mK]	0,661	
λ_s3 [W/mK]	0,765	
Step 4	Calculating bottom+ Step 3	Parallel + serial method (mean value)
V_3	0,800	
V_bottom	0,200	
λ_3 [W/mK]	0,765	
λ_bottom [W/mK]	1,000	
λ_p4 [W/mK]	0,812	
λ_s4 [W/mK]	0,802	
λ_m4 [W/mK]	0,807	
Step 5	Calculating mortar joints + step 4	Parallel + serial method (mean value)
V_4	0,916	

V_joint	0,084
λ_4 [W/mK]	0,807
λ_joint [W/mK]	1,000
λ_p5 [W/mK]	0,823
λ_s5 [W/mK]	0,820
λ_m5 [W/mK]	**0,822**

4. APPENDIX 4 – GRANULOMETRY BOUDRY

étude: analyse granulométrique / méthode par tamisage à sec après lavage (NFP 94-056) (° 80mm)

identification: échantillon 3 / Terre de Boudry

Teneur en eau	**Condition et préparation d'essai**
Masse humide = g	Lavage des essais: jet d'eau
Masse sèche = g	Séchage (NFP 94-050): à l'étuve au moins 4heures à 105 ± 5°C
Teneur en eau = 2.23%	

Masse de l'échantillon sec M, (g)		3403		
			Pourcentage	
Tamis (mm)	**Module AFNOR**	**Masse des refus cumulés (g)**	**Refus**	**Passants**
80	50			
63	49			
50	48			
40	47			
31.5	46			
25	45			
20	44	0	0	100
16	43	19	0,5583330885	99,44166912
12.5	42	27	0,793417573	99,20658243
10	41	32	0,940346753	99,05965325
8	40	42	1,234205113	98,76579489
6.30	39	52	1,528063473	98,47193653
5	38	73	2,14516603	97,85483397
4	37	101	2,967969439	97,03203056
3.15	36	171	5,024977961	94,97502204
2.50	35	263	7,728474875	92,27152512
2	34	361	10,60828681	89,39171319
1.60	33	496	14,57537467	85,42462533
1.25	32	678	19,92359683	80,07640317
1	31	834	24,50778725	75,49221275
0.800	30	965	28,35733177	71,64266823
0.630	29	1080	31,73670291	68,26329709
0.500	28	1199	35,2336174	64,7663826
0.400	27	1310	38,4954452	61,5045548
0.315	26	1415	41,58095798	58,41904202
0.250	25	1491	43,81428152	56,18571848
0.200	**24**	**1560**	45,8419042	54,1580958
0.160	23	1629	47,86952689	52,13047311
0.125	22	1697	49,86776374	50,13223626
0.100	21	1736	51,01381134	48,98618866
0.080	**20**	**1783**	52,39494564	**47,60505436**

identification: échantillon 3 / Terre de Boudry

Masse totale de l'échantillon sec après lavage au tamis 80µm: ML (g)= 358,3

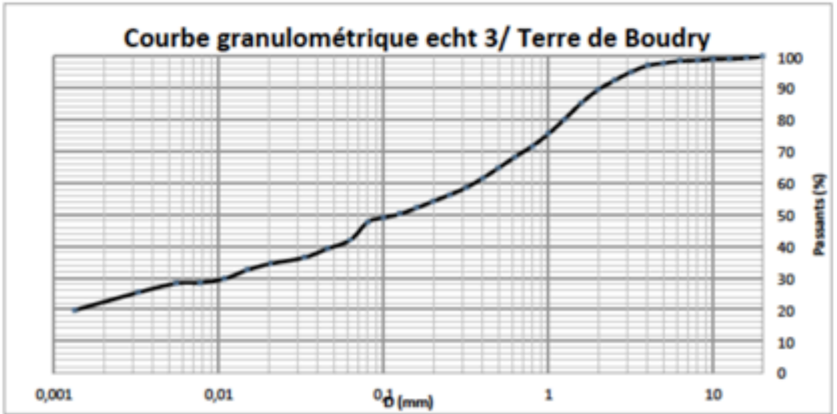
D (mm)	p' (%)
0,00132936	19,75268583
0,003270253	25,42555682
0,005560536	28,25019939
0,007676781	28,50030384
0,010725996	29,62902875
0,014869165	32,45084101
0,020625206	34,4731398
0,032896785	36,35434797
0,045556325	39,17616023
0,063029525	41,9979725
0,08	47,60505436
0,1	48,98618866
0,125	50,13223626
0,16	52,13047311
0,2	54,1580958
0,25	56,18571848
0,315	58,41904202
0,4	61,5045548
0,5	64,7663826
0,63	68,26329709
0,8	71,64266823
1	75,49221275
1,25	80,07640317
1,6	85,42462533
2	89,39171319
2,5	92,27152512
3,15	94,97502204
4	97,03203056
5	97,85483397
6,3	98,47193653
8	98,76579489
10	99,05965325
12,5	99,20658243
16	99,44166912
20	100

étude: analyse granulométrique / méthode par sédimentation (NFP 94-057) (≤ 80mm)

Masse totale de l'échantillon sec : M_s (g)= 343,3
Pourcentage de passants à 80µm: 47.605%
Masse de la prise d'essai sur le tamisat à 80µm: m (g)= 80 ±10
Section de l'éprouvette d'essai: 48,30 cm²
Réalisation de l'essai

Temps (s)	Densimètre R	Température q	C_t (q)	r_w (q)	Nbr de poiseu	H_t (m)	D (µm)	D (mm)	r_t (q)	p	p (%)	p'	p' (%)
30	1,023	26	0,001325	997	0,000884212	0,127525	63,02952464	**0,063029525**	1019,258025	0,882217677	88,22176766	0,419979725	**41,9979725**
60	1,0215	26	0,001325	997	0,000884212	0,13324	45,55632471	**0,045556325**	1017,762525	0,822942133	82,29421329	0,391761602	**39,17616023**
120	1,02	26	0,001325	997	0,000884212	0,138955	32,89678521	**0,032896785**	1016,267025	0,763666589	76,36665891	0,36354348	**36,35434797**
300	1,019	26	0,001325	997	0,000884212	0,13655382	20,62520588	**0,020625206**	1015,270025	0,72414956	72,41495599	0,344731398	**34,4731398**
600	1,018	25,5	0,00125	997	0,000894153	0,14036382	14,86916514	**0,014869165**	1014,19825	0,681668754	68,16687535	0,32450841	**32,45084101**
1200	1,0165	25,5	0,00125	997	0,000894153	0,14607882	10,72599582	**0,010725996**	1012,70275	0,62239321	62,23932097	0,296290287	**29,62902875**
2400	1,016	25	0,00115	997	0,000904269	0,14798382	7,676780543	**0,007676781**	1012,10455	0,598682992	59,86829922	0,285003038	**28,50030384**
4800	1,015	24	0,001	997	0,000925045	0,15179382	5,560535797	**0,005560536**	1011,972	0,593429249	59,34292488	0,282501994	**28,25019939**
14400	1,0135	24	0,001	997	0,000925045	0,15750882	3,270253411	**0,003270253**	1010,475	0,534094251	53,40942511	0,254255568	**25,42555682**
86400	1,011	27	0,0015	997	0,000864843	0,16703382	1,329360433	**0,00132936**	1007,4685	0,414928806	41,49288065	0,197526858	**19,75268583**

C_t (q):facteur correcteur de température
r_w (q): masse volumique de l'eau distillé à la température d'essai q
H_t: profondeur effective du centre de poussée du densimètre
D: diamètre équivalent des plus grosses particules non sédimentées à l'intant t (lecture sur le densimètre)
r_t: masse volumique de la suspension à l'instant t
p: pourcentage d'éléments inférieurs ou égaux à D (par rapport à la masse sèche de la prise d'essai)
p': pourcentage d'éléments inférieurs ou égaux à D (par rapport à la masse sèche totale de l'échantillon)



5. APPENDIX 5 – HOT PLATE METHOD

Values of heat recistance through thin air layers. Adjusting parameter for calculations of the Hot plate method.

Résistance thermique d'une couche d'air non ventilée.

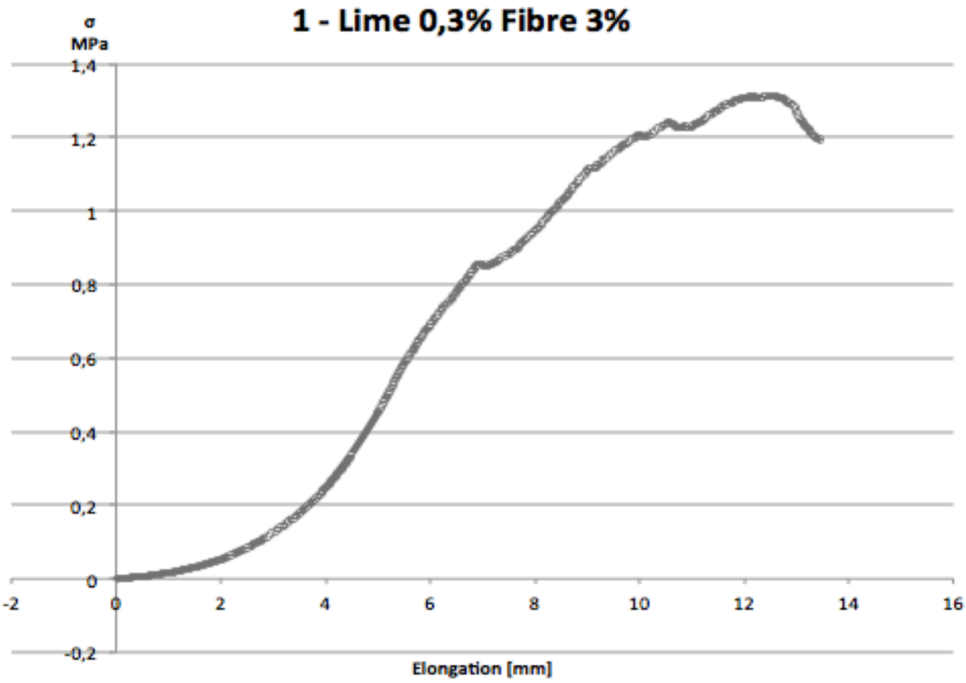
Épaisseur de la couche d'air	Couche d'air verticale	Couche d'air horizontale Flux de chaleur vers le haut	Couche d'air horizontale Flux de chaleur vers le bas
1 mm	0,035 m²K/W	0,035 m²K/W	0,035 m²K/W
5 mm	0,110 m²K/W	0,110 m²K/W	0,110 m²K/W
10 mm	0,150 m²K/W	0,130 m²K/W	0,150 m²K/W
20 mm	0,170 m²K/W	0,150 m²K/W	0,200 m²K/W
50 mm	0,170 m²K/W	0,150 m²K/W	0,210 m²K/W

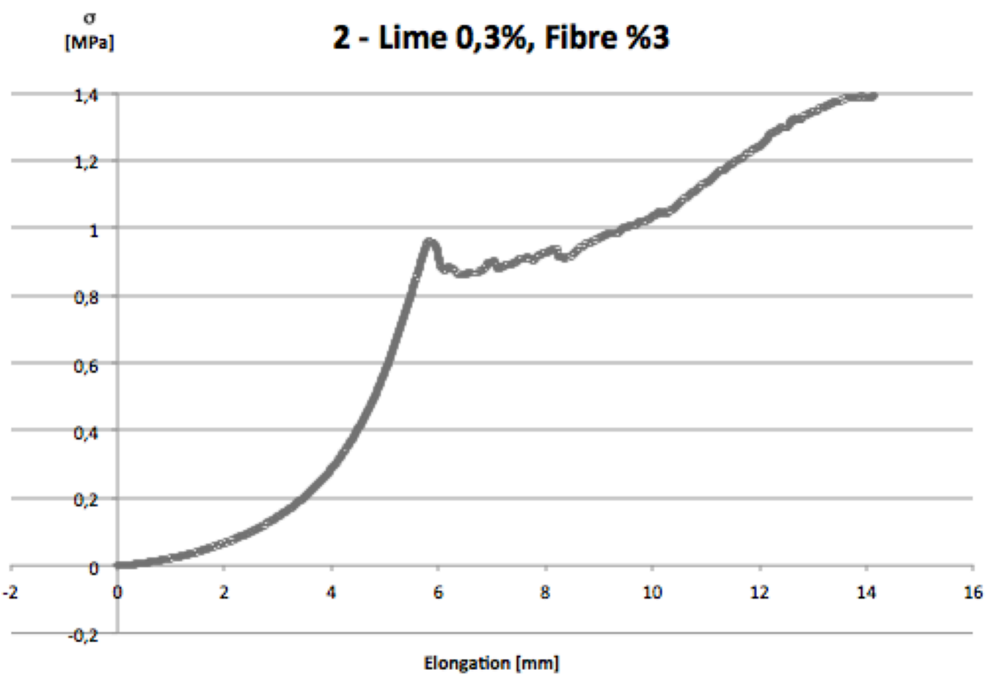
Résistance thermique d'une couche d'air peu ventilée.

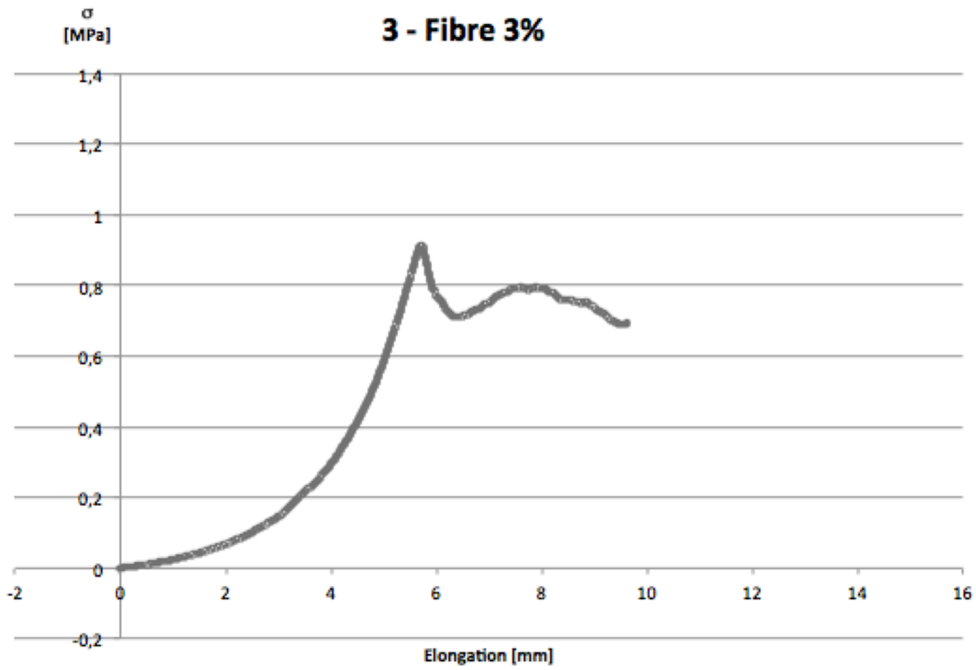
Épaisseur de la couche d'air	Couche d'air verticale	Couche d'air horizontale Flux de chaleur vers le haut	Couche d'air horizontale Flux de chaleur vers le bas
1 mm	0,017 m²K/W	0,017 m²K/W	0,017 m²K/W
5 mm	0,055 m²K/W	0,055 m²K/W	0,055 m²K/W
10 mm	0,075 m²K/W	0,065 m²K/W	0,075 m²K/W
20 mm	0,085 m²K/W	0,075 m²K/W	0,100 m²K/W
50 mm	0,085 m²K/W	0,075 m²K/W	0,105 m²K/W

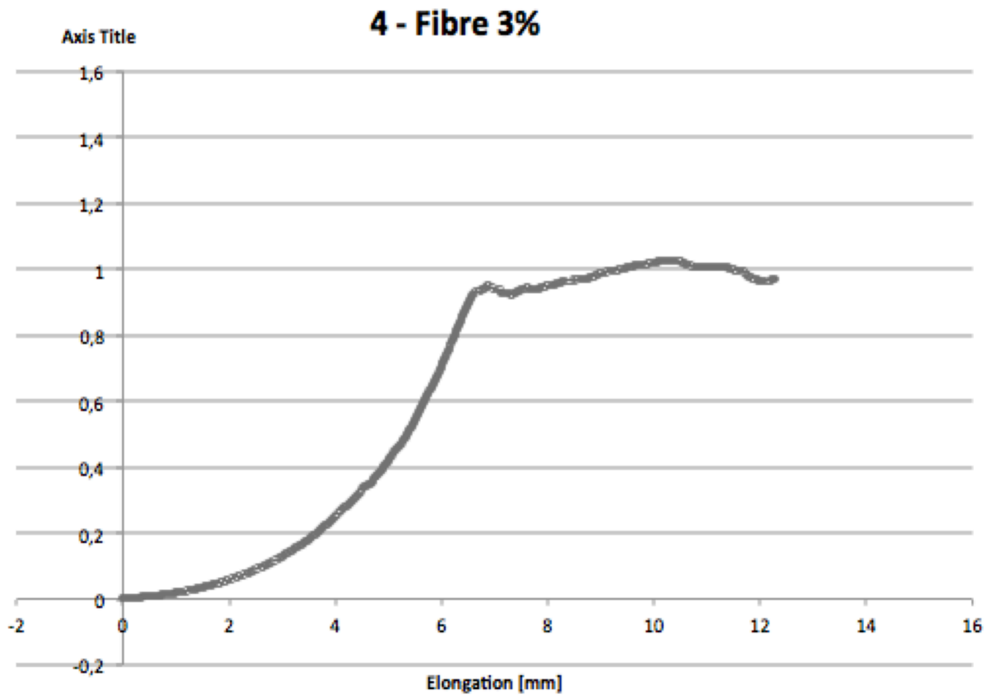
6. APPENDIX 6 – TENSILE STRENGTH

Chart of the results from the tensile test experiment. Two samples with lime and fibre and two samples with only fibres






σ
[MPa]
3 - Fibre 3%
1,4
1,2
1
0,8
0,6
0,4
0,2
0
-0,2
-2
0
2
4
6
8
10
12
14
16
Elongation [mm]


Axis Title
4 - Fibre 3%
1,6
1,4
1,2
1
0,8
0,6
0,4
0,2
0
-0,2
-2
0
2
4
6
8
10
12
14
16
Elongation [mm]