School of Science and Engineering

Capstone Report

THERMOEFFICIENT BUILDING MATERIAL FOR A HOUSE IN GUIGOU

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THERMO-EFFICIENT BUILDING MATERIAL FOR A MODEL HOUSE IN GUIGOU

Final Capstone Report – Oussama Amine

Supervised By

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Abstract

This capstone project will attempt to find the most thermo-efficient building material to be used in houses in the village of Guigou in the Ifrane province. The main goal is to increase the quality of life of residents during winter, respecting the main constraint which is the cost.

This project will consist of three parts. The first one will be focused grasping the concepts related to building and the materials used in building and insulation. The second will be focused on the analysis of different building materials by looking to the thermal conductivity and making process of each material. This part will include combining and juxtaposing different building materials but also material making processes in order to get to the desired properties which are making the walls insulting enough to attain thermal control. The third part will focus on the analysis of the real life energy consumption required to keep thermal control for each of the alternatives, using the software Design Builder.
Introduction

In recent years, people worldwide noticing the effects of the negligence of the environment from our behalf. We live in a planet which an “Ecosystem”. The latter includes all components of the environment such as the atmosphere, the seas and oceans, and the living things inclusive of humans. Our activities, especially the industrial activity has caused many problems in our ecosystem. The main ones being Pollution, Climate change, and Global Warming. [3]

Pollution is now present all around the globe and it includes, water pollution, air pollution, soil pollution, and light pollution, amongst others. All of which have been caused by humans. For instance, water is mainly polluted by waste dumping and oil spills, air pollution is caused by burning fuels, while light pollution is manifested in light trespass, which the undesired light that sneaks in our rooms at night. [3]

Although Climate change is doubted by many people, it remains of the biggest environmental problems humans have caused. It has not only multiple obvious consequences such as global warming and greenhouse effects, but also unexpected consequences such as the vanishing of polar ice and the emergence of diseases. [3]

As for Global Warming, it is the rise in the average global temperature because of the greenhouse gases, which include CO2 and water vapor. Those gases are necessary to maintain a life-friendly temperature on the surface of the planet as they can keep heat, however, in if present in big quantities they turn up the temperature to higher than needed. Their presence in our atmosphere in high quantities is mainly due to industrial activity. [3]
Faced with these problems, governments and scientists have started considering a new concept called sustainable development. A simple definition of the latter can be formulated as follows: Meeting our generations’ needs, without jeopardizing the capacity of our natural resources to provide the needs of future generations. [4]

The main goal behind sustainable development is the integration of its three dimensions in a successful economy, providing social benefits, while preserving high quality environment, as shown in Figure 1. [5]

![Figure 1: Three Dimensions of Sustainability](image)

Although all three pillars are hard to achieve, the hardest one to maintain remains the environmental pillar. [5] In two past decades, Morocco has made appreciable advancements towards reaching sustainability, especially with regard to the environment. The government has
been funding and encouraging projects related to the shifting to renewable energies with the aim of reducing the emission of greenhouse gases.

In order to decrease the emissions of greenhouse gases, we can improve the insulation of walls in regions that suffer from cold weather, which will decrease the amount of combustibles used, ultimately reducing the amounts of gases emitted to the air and decreasing the amount of air pollution.

1. Project Description:

In the region of Ifrane, especially the village of Guigou, temperatures in the winter reaches -5°C at night due to the snowfall. [2] Those temperatures make the life of the residents of the village hard as they have to heat up the house, particularly during the night. The methods they typically use to heat up the house are wood, coil, or gas. When using wood, they tend to either use a fireplace, if they have one installed, or an old woodstove.
When using coil, they typically use a coil stove such as the one shown below:

![Coil Stove](image)

*Figure 4: Coil stove*

As for gas, they typically use a gas heater like the one in the picture below:

![Gas Heater](image)

*Figure 1: Gas Heater*
All of the heating methods mentioned above represents asphyxiation risks as they are mostly old and therefore do not have proper asphyxiation prevention systems. In addition, people tend to use them while ignoring the safety precautions such as leaving a slightly open window to keep air flowing, or opening the door for one minute every 30 minutes. The result is that we keep hearing that whole families died asphyxiated every winter, and their numbers appears to be increasing every year.

The reason behind those tragedies is that they keep using the heaters for an extended period of time, mainly because the types of building materials used, such as cement or concrete, are not thermo-efficient, therefore allow a huge quantity of heat to escape through the walls. By consequence, the heat generated by the heaters keep escaping, preventing the heat from building up in the house until it reaches the desired temperatures. In contrast, if the building materials used were thermo-efficient, the amount of heat escaping through the walls would be minimal allowing the heat to build up in the house until it reaches the desired temperatures. Then the heater can be turn off for a while, until the temperatures drops again, before being turn on again, minimizing not only the time that the heaters are used, thus reducing the risk of asphyxiation, but also the cost of the fuel.

2. STEEPLE Analysis:

When it comes to strategic planning tools, there are multiple alternatives to choose from. Although the SWOT analysis is the most common technique used, other techniques such as the STEEP, PEST, and STEEPLE, with the latter being the broadest as it analyzes the impact on more dimensions. Its letters stands for the following words: Social, Technological, Economic, Environmental, Political, Legal, and Ethical. [1]
This analysis allows us to have a better view of how this project will affect the external environment, which will help us better recognize the constraints that we will be facing while following through this project.

A. Social Impact:

The social impact of this project consists of the families living in Guigou as this project will help them to better face the cold of winter, as their home will be retaining more heat, and reduce their heating costs which will improve their buying ability and reduce the risks related to heating by burning wood or using gas. It will also improve the quality of their life meaning that they would live in warmer houses in the winter with lower risks of suffocating.

B. Technological Impact:

The technological impact of this project will revolve around the software used to simulate the multiple mixtures and to collect experimental data, namely Design Builder and BenchLink. It will also include the methods used to make the bricks.

C. Environmental Impact:

The environmental impact is directly relating to heating. The current heating methods used by the residents of Guigou are burning wood, coil, or gas. Finding the most thermo-efficient building material will allow for less use of the conventional heating methods. These methods produce high level of greenhouse gases which contribute to the global warming. This project will help reduce the amounts of wood and gas burned meaning there will be a reduction in the amount of greenhouse gases produced and the number of trees cut to produce wood.
D. Economic Impact:

The economic implications of this project can be summarized in the reduction of the energy bills, which includes electricity, gas, coil, and wood, leaving them with more money for their other expenses. On the other hand, as the materials used in the making of the bricks is cheap, there will be a reduction in the building costs.

E. Political Impact:

This project is a step towards the direction pointed by the Moroccan government, which is called “Green Morocco”. The main idea is to move towards sustainable development in all fields, including energy and construction, under which this project falls.

F. Legal Impact:

As for the legal implications, this project will be respecting the regulations drawn by the laws of this country in terms of safety standards.

G. Ethical Impact:

Lastly, the ethical impact of this project means that I should keep my supervisor and the people of Guigou aware of the work done, the materials used, and the progress. It also means that I must respect academic integrity in conducting this project.
Methodology

The aim of this project is to find the most thermo-efficient building material to be used in houses in the village of Guigou in the Ifrane province. The feasibility study is a mandatory analysis that needs to be conducted before starting any form of project, as it focuses on whether the latter is workable and achievable in the time frame given or not.

Since the project will focus on choosing the suitable building material to withstand the cold of snow, considering the insulating properties and technologies that could reduce the heat exchange which will decrease wasted energy. There are two main constraints facing this project.

The first constraint is the weather. The weather in the region is pretty harsh as it gets to very low temperature in the winter and high temperature in the summer. We can find materials which are thermo-efficient which can withstand the cold weather, but cannot withstand the heat of the summer and thereby, they are not suitable for the weather in the region.

The second constraint is the cost. The residents of the village of Guigou are mostly in difficult financial situations, therefore, the materials used needs to be cheap. The best quality materials can be quite expensive and it will be difficult to find low cost materials that will fit the requirements. In addition, the few low-cost good quality materials that exist re hard to come by in Morocco and the cost of importing them is high.

The first step to be taken in this project is the same as in any other engineering project. I need to start by grasping the full pictures of building a house. This is done through conducting
a literature review which requires studying previous works done on this subject in order to identify the different materials used in making bricks and insulation. I also need to identify their constitution and properties, in addition to the benefits and drawbacks of using each one. This step will help me identify the materials I can use.

The second step consists of conducting the appropriate experiments to identify which material is most thermos-efficient. I will first start by creating multiple bricks with different compositions, then conduct experiments on multiple types of bricks in order to discover the thermal properties of each type of bricks. As our university does not have the proper equipment for some of the experiments I need to conduct, the flash method and the hot plate method. Therefore, I had to visit the ESTS, where Dr. Khebbazi, a professor there, helped me conduct the experiments.

The third step consists of running a simulation in Design Builder. I will create a model house using the software, then try it with the different types of bricks in order to find the optimal one as specified by Design Builder.
Literature Review

When discussing thermal properties of a material, there are five main properties that need to be checked. Those properties are the Density, the Thermal Conductivity, the Specific Heat Capacity, the Thermal Diffusivity, and the Thermal Effusivity. As for mechanical properties, we are interested in the compressive strength. In the next section, I will define each one of them then present the way we can calculate them.

1. Thermal Properties:

   A. Density:

   The density represents the mass of a substance per unit volume. If we have the volume (V) and the mass (m) of an object, we can easily calculate it density (d) using the following formula:

   \[ d = \frac{m}{V} \]

   However, if we do not have the volume of an object whose shape is irregular, we can use the water volume variation method, which consists of submerging the object in a water container for five seconds. The increase in the volume of the water represents the volume of the object. The operation should not exceed five seconds to keep the quantity of water that absorbed into the object negligible.

B. Thermal Conductivity:

This property represents the rate at which heat is transferred through a material. The formula to calculate thermal conductivity (k) is the following:

\[ k = \frac{Q \cdot L}{A \cdot \Delta T} \]
Where $Q$ is the amount of heat transfer through the material, $L$ is the width of the material, $A$ is the area of the material, and $\Delta T$ is the difference in temperature.

The experiment done to find the thermal conductivity is called the centered hot plate method. It consists of placing the sample between an aluminum block and insulation foam followed by an aluminum block as shown in the Figure 2 below:

![Figure 5: Asymmetrical Hot Plate Method](image)

The formula used to calculate the thermal conductivity through this experiment is the following:

$$k = \frac{e_1}{T_0 - T_1} \times \left( \frac{U^2}{R \times S} - \frac{\lambda_2}{e_2} \times (T_0 - T_2) \right)$$
Where \( e_1 \) is the thickness of the sample, \( U \) is the voltage, \( R \) is the resistance, \( S \) is the area of the heating plate, \( e_2 \) is the thickness of the insulating foam, and \( \lambda_2 \) is the thermal conductivity of the insulating foam.

C. Thermal diffusivity:

Thermal diffusivity represents the rate at which heat is transferred at a constant pressure point. The formula used to calculate it is the following:

\[
\alpha = \frac{k}{d \cdot C_p}
\]

The experimental method used to find it is called the Flash method. The way it is conducted is that we stabilize the sample at a temperature \( T_0 \), then we proceed to irradiate the front of the sample with high-energy blast coming through a laser. We then measure the increase in temperature, which plotted with respect to time. Figure 3 represents the experiment, while Figure 4 represents the resulted graph with multiple samples tested:
The temperature curve typically rises but with increased heat loss, the temperature of the back surface decreases after peaking to the maximum as we can see in the B and C curves. Otherwise, the temperature of the rear surface keeps on increasing until it reaches its maximum where it stays as we can see in curve A.

The curve is generated through a computerized program called BenchLink which offers a graph as depicted in Figure 5:

Figure 7: Increase in Temperature for Multiple Samples

Figure 8: Thermogram through BenchLink
The formula used to calculate the thermal diffusivity was created by Parker and it uses the time the sample needed to reach half the maximum temperature ($T_\frac{1}{2}$):

$$\alpha = 0.1388 \frac{L^2}{T_\frac{1}{2}}$$

As this formula requires ideal sample conditions, it is rather limited. Therefore, we can also use the De Giovanni equations:

$$\alpha = \frac{L^2}{T_\frac{5}{6}} \left( \frac{0.15 \cdot T_\frac{5}{6} - 1.25 \cdot T_2}{3} \right) + \frac{L^2}{T_\frac{5}{6}} \left( \frac{0.76 \cdot T_\frac{5}{6} - 0.926 \cdot T_2}{3} \right) + \frac{L^2}{T_\frac{5}{6}} \left( \frac{0.618 \cdot T_\frac{5}{6} - 0.862 \cdot T_2}{3} \right)$$

D. Specific Heat Capacity:

The Specific Heat Capacity represents the amount of energy required to change the temperature of one kilogram of a substance by 1°C. It is calculated through the following formula:

$$C_p = \frac{k}{d \cdot \alpha}$$

E. The Thermal Effusivity:

The Thermal Effusivity measures a material’s capacity to exchange heat with its environment. It is calculated through a formula which combines the density, the thermal conductivity, and the specific heat capacity as follows:

$$e = \sqrt{d \cdot k \cdot C_p}$$

As for measuring it experimentally, we can use a thermal effusivity sensor.
2. Mechanical Properties:

The mechanical property we are particularly interested in is the compressive strength. This property represents the ability of a material to withstand loads under compression, which tend to reduce the size of the material. At their compressive strength limit, materials tend to fracture. This limit is also called the ultimate compressive strength or yield compressive strength.

Compressive strength is calculated experimentally through an experiment called compressive stress test. The sample is put in a press as the one shown in Figure 9. The machine keeps increasing the load on the sample until it breaks, then it displays the maximum load. The maximum load $P$ is then divided by the area of the sample $A$ to get the compressive strength $S$ as shown in the following formula:

$$S = \frac{P}{A}$$

*Figure 9: Compressive Strength Testing Machine*
Our brick needs to meet the national standards of compressive strength in order to be able to withstand the weight of the building. Since Morocco does not have any norms in terms of the minimum compressive strength required, I chose to work with the European norms, which state that a brick needs to have a minimum of 10MPa of compressive strength. [8]

3. Building Materials:

The use of bricks is widely spread in construction nowadays because it offers many advantages. Bricks come in all shapes and colors which makes them aesthetic. It has high compressive strength making them strong. They also offer great porosity as they can take in and give out moisture giving them great humidity and temperature regulators. In addition, they offer protection in case of fire up to 6 hours. Another advantage of using bricks is sound isolation as they usually prevent sound from getting in the building.

Furthermore, bricks offer outstanding thermal insulation as they direct and keep up inside temperatures of the building because of their ability to absorb and gradually discharge heat. As a result, they can help reduce energy waste up to 35% contrasted with wood. Besides, it provides wear resistance and durability.

As for the types of bricks, there exists 5 types which are common burnt clay brick, sand lime brick, engineering bricks, concrete bricks, and fly ash clay bricks.

A. Common Burnt Clay Bricks:

Common burnt clay bricks are composed out of normal clay which is compressed in a mold. This compression is responsible for their particular rectangular shape. The raw clay used to
make the bricks is soft and is left to dry for a while after it is molded, before being fired in an oven. As common clay bricks are not aesthetic, they require to be plastered then painted to give them an appealing look. The density of common burnt clay bricks can vary between 1200 kg/m³ and 1900 kg/m³. Shown below is a picture of a common burnt clay brick.

![Figure 10: Common Burnt Clay Brick](image)

**B. Sand Lime Bricks:**

Sand Lime Bricks are bricks made with sand, lime, and fly ash. The components are mixed then chemically processed to create a paste. The latter is put in a pressurized mold to create the desired brick. The sand lime brick is advantageous compared to the common burnt clay brick as it has a smoother finish making it able to do without plastering, in addition to being stronger. Their density can vary from 910 kg/m³ to 2200 kg/m³.
C. Engineering Bricks:

Engineering bricks are fired at super high temperature, which makes them denser and stronger. Those properties reduce the absorption of water by the bricks, making them able to bear extreme loads. The problem with these bricks is that they are expensive, therefore, cannot be used everywhere. Their density can vary from 2200 kg/m³ to 2350 kg/m³.
D. Concrete Bricks:

Concrete Bricks are the most commonly used bricks in Morocco. They are made out of concrete and come in multiple colors. They are mostly placed in fences or façade for their outstanding aesthetic look. The density of concrete bricks can vary from 1900 kg/m$^3$ to 2100 kg/m$^3$.

![Concrete Bricks](image13.png)

Figure 13: Concrete Bricks

E. Fly Ash Clay Bricks:

Fly Ash Bricks are bricks made with fly ash and clay. They are mixed then modeled and fired at more than 1000 °C. The problem with this type of bricks is that they decrease the water sealing, thus inflicting damage to the structure. Their density tend to vary between 1700 kg/m$^3$ and 1850 kg/m$^3$. 
4. Thermal Insulation Materials:

There exists many types of thermal Insulation materials. There are the clumsy fiber materials, for example, fiberglass, slagwool, and cellulose. Then there are rigid foams and sleek foils. Thanks to the air and other gases trapped inside them, these materials have the property of resisting both conductive and convective heat transfer in a structure. As for reflective foils, they are used in reflective insulation systems because of their ability to resist radiant heat. [6]

The thermal insulation materials typically used in Morocco are Fiberglass, Rockwool, Cellulose, Cork, Sheep Wool, Straw, and Sawdust.

A. Fiberglass:

Fiberglass is made of very thin glass fibers and is regarded as the most widely spread insulation materials. It comes in two types, either fiberglass rolls or fiberglass batts.
Fiber glass is manufactured by mixing and stirring glass and sand at a very high temperature exceeding 1500°C. The stirring is responsible for the creation of the form of the fiberglass shown in Figure 16. The biggest advantage of using this material is that it is incombustible making it safer than other combustible alternatives in case of blaze. As for its worse disadvantage, it is the fact that it contains, in some cases, a phenol formaldehyde binder, which is a carcinogenic toxic substance. [7] The thermal conductivity of fiberglass varies from 37 mW/m.K to 55mW/m.K depending on its density and humidity.

B. Cellulose:

Cellulose is a material made mostly from paper products, recycled newspaper to be precise. It is manufactured by cutting paper into tiny chunks which then go through a process called fiberization. The latter gives the cellulose its airflow inhibiting and thermal insulation properties. Although cellulose is cheaper to buy than fiberglass, the installation cost of Cellulose is higher than that of Fiberglass. Its thermal conductivity is about 40mW/m.K.
Rockwool is a material who is almost identical to fiberglass. It is manufactured using natural minerals such as chalk and basalt or diabase. The components are mixed at 1600°C making them a coulee which is then spun to produce fibers. The latter are compressed in the form of a mat than can be cut to the desired shape. It contains, on average, 75% of recycled industrial waste. Rockwool is a good thermal insulator as it can keep a good insulation even if its humidity level rises. In addition, it is also a good sound insulator. Its downsides is that it is flammable and can cause irritation and lung cancer. Its thermal conductivity is about 44mW/m.K.
D. Sheep Wool:

Sheep wool is also used as insulation. In order to be prepared for use, it is treated using borate which makes it pests, fire, and mole resistant. Its advantages is that it is reusable, it filters the air from harmful gases such as Nitrogen and Sulfur Dioxide, it can hold huge amounts of water which is desired in some cases, and it provides sound insulation as well. The downside however, is that it loses the borate if wetted too many times. Its thermal conductivity varies between 35mW/m.K and 58mW/m.K.

![Sheep Wool](image)

Figure 19: Sheep Wool

E. Cork:

Cork is extracted from Cork Oak trees, which are widely available in Mamora forest in Rabat. The cork is the external layer of the tree. It is removed from the tree in planks which are treated using mater and heat to clean them from dirt and undesirable components. Afterwards, the planks are trimmed to the well-known shape to give the final usable product. Among its advantages, we find the fact that it is hypoallergenic, which makes it a great choice for people suffering from allergies. Its thermal conductivity is about 40mW/m.K.
F. Straw:

Straw is a popular cheap and easy to come by alternative for insulation. It comes from agricultural waste. Once the farmers have extracted the grains, the left bale is sold in order to become insulation material. The advantage of using straw is that it delays fire as it can block oxygen from getting in, in addition to being a cheap way to create thick walls which usually expensive using different materials. The thermal conductivity of straw varies between 44mW/m.K and 63mW/m.K and its density between 35Kg/m$^3$ and 190Kg/m$^3$. 
G. Sawdust:

Sawdust is a leftover product of cutting, grinding, drilling, and sanding of wood using various tools. It is the most cost effective alternative as it provides the higher insulation-to-cost ratio. In order to render it usable for walls insulation, it needs to be buffered with hydrated lime, which a preservative, an insecticide, and a dehydrator. The thermal conductivity of sawdust is significantly higher than other alternatives discussed as it is more or less 80mW/m.K.

*Figure 22: Sawdust Insulation*
Experimental Study

In order to conduct the experimental study, first I have to make the samples. I believe it would be best to choose the clay from Guigou, since the bricks will be made there.

1. X-ray Diffraction and X-ray fluorescence:

In order to determine the composition of the clay there, X-ray diffraction and fluorescence X had to be conducted on the sample. Figure 23 and Table 1 below represent the results of the X-ray diffraction and X-ray fluorescence respectively:

![Figure 23: X-ray Diffraction Results](image)

<table>
<thead>
<tr>
<th>Chemical Components</th>
<th>Percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$SiO_2$</td>
<td>59.2</td>
</tr>
<tr>
<td>$Al_2O_3$</td>
<td>22.4</td>
</tr>
</tbody>
</table>
Through the composition, we can see that the constitution of the clay include Alumina, which is $Al_2O_3$, Quartz, which is $SiO_2$, and Mica, which is K, Fe, Mg, and Al. I was also able to find the chemical formula of the clay which is the following:

$$(K, H_3O)(Al, Mg, Fe)2(Si, Al)4O10[(OH)2(H2O)]$$

The clay contains a high percentage of Illite, while Kaolinite is slightly present meaning that the clay can be considered Illite. Illite is a clay mineral of a group resembling micas, with a lattice structure which does not expand on absorption of water. It is an advantage as Illite clay offer reduced shrinkage, low flexibility, and low absorption of water, since infiltration of water between the octahedral and tetrahedral sheets is prevented by the K+ ions which fix the void between those sheets.

In addition, Illite is chemically stable and is a good thermal and electrical insulator. Moreover, it has high compressive strength. Figure 24 represents the structure of Illite. The atoms in green represents an isomorphous substitution within the tetrahedral sheet.
I chose to combine straw with clay for the advantages that straw offers. Straw is a good thermal insulator, in addition to being cheap. Furthermore, it is easy to come by in Guigou as almost all the residents are involved in agricultural activity. I also measured the density of the clay and found it to be:

\[ d = \frac{m}{V} \]

\[ d = \frac{1Kg}{5.344 \times 10^{-4}m^3} \]

\[ d = 1871.26Kg/m^3 \]

2. Creation of samples:

In order to create the samples, I went to Guigou where I found a man who has been making clay bricks for decades and asked him to make four different samples, with different percentage of clay and straw. Knowing the exact volume of the sample is a primordial information if I am
to know the exact amounts of both clay and straw to put in each mixture. With this aim, I measured the dimensions of the mold used by the man which were 16.5cm*16.5cm*39cm. Then I calculated the mass needed to fill the mold for each material. The results are shown in Table 2.

Table 2: Densities of the materials and the mass required to fill the mold

<table>
<thead>
<tr>
<th>Material</th>
<th>Mold’s Volume</th>
<th>Material’s Density (Kg/m³)</th>
<th>Mass required to fill the mold (Kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay</td>
<td>10617.75cm³</td>
<td>1871.26</td>
<td>19.87</td>
</tr>
<tr>
<td>Straw</td>
<td>10617.75cm³</td>
<td>39.86</td>
<td>0.423</td>
</tr>
</tbody>
</table>

After letting them dry for five days, I fired them in an oven at 45°C to make sure no humidity is left. As the bricks will have to withstand the weight of the walls and the weight of the roof, they need to have a compressive strength equal to or higher than 10Mpa.

A. Sample 1:

For the first sample, I decided to mix 2% of straw and 98% of clay.
B. Sample 2:

For the second sample, I decided to mix 4% of straw and 96% of clay.

Figure 26: Sample 2

C. Sample 3:

For the third sample, I decided to mix 8% of straw and 92% of clay.

Figure 27: Sample 3
D. Sample 4:

For the fourth sample, I decided to create a different kind than the first three. This one will be made with a mixture of 4% of straw and 96% of clay, but will be composed of three layers, a layer of pure straw comprised between two layers of the mixture. This layer layout will increase significantly the thermal insulation.

![Sample 4](image)

Figure 28: Sample 4

3. Results and Discussion:

A. Density:

In order to calculate the densities, I had to weight each sample and to measure their dimensions. Table 3 represents the results:

<table>
<thead>
<tr>
<th>Samples</th>
<th>Densities (Kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1834.93</td>
</tr>
</tbody>
</table>
The densities of the samples vary from 1212.15\( Kg/m^3 \) and 1834\( Kg/m^3 \). The biggest density is that of Sample 1 as it contains the most amount of clay which is denser than straw. We can also see that Sample 4’s density has decreased drastically because of the straw interlayer.

### B. Thermal Conductivity:

The next step after finding the densities is to calculate the thermal conductivity. In order to compute it, I used the centered hot plate method, using polystyrene insulation foam, whose thermal conductivity \( \lambda_2 \) equals 40mW/m.K. Its thickness \( e_1 \) and surface A equal 0.0102m and 0.006435\( cm^2 \), respectively. As for the power source, its current and voltage were equal to 0.15A and 6V, respectively. The experiment yielded the necessary temperatures through Benchlink which are the following:

<table>
<thead>
<tr>
<th>Value</th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
<th>S4</th>
</tr>
</thead>
<tbody>
<tr>
<td>( e_1 (m) )</td>
<td>0.165</td>
<td>0.165</td>
<td>0.165</td>
<td>0.165</td>
</tr>
<tr>
<td>Average ( T_0 ) (°C)</td>
<td>30.02</td>
<td>29.78</td>
<td>30.15</td>
<td>31.47</td>
</tr>
<tr>
<td>Average ( T_1 ) (°C)</td>
<td>26.72</td>
<td>25.86</td>
<td>23.75</td>
<td>25.92</td>
</tr>
<tr>
<td>Average ( T_2 ) (°C)</td>
<td>21.7</td>
<td>20.8</td>
<td>20.09</td>
<td>21.8</td>
</tr>
</tbody>
</table>
From Table 4, the best sample in terms of thermal insulation is the sample 4 with a thermal conductivity of 0.04 W/m.K thanks to its straw interlayer. The second best was the sample 3 as it has 4% straw with a thermal conductivity of 0.2 W/m.K. The third best was the sample 2 with a thermal conductivity of 0.63 W/m.K. The worst of them was the sample 1 with a thermal conductivity of 0.77 W/m.K, as it contains the less amounts of straw.

C. Thermal Diffusivity:

In order to minimize the error, I placed the samples in the box until the temperatures stabilized in BenchLink. After that, I took the temperatures every 5 seconds which were plotted. After that I used the formula provided before to calculate the thermal diffusivity of each sample. The results are shown in Table 4:

<table>
<thead>
<tr>
<th>Samples</th>
<th>( \frac{T}{2} ) (s)</th>
<th>L (m)</th>
<th>Thermal Diffusivity ( \alpha ) (m(^2)/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>12986</td>
<td>0.165</td>
<td>2.91*10^{-7}</td>
</tr>
<tr>
<td>2</td>
<td>14478</td>
<td>0.165</td>
<td>2.61*10^{-7}</td>
</tr>
<tr>
<td>3</td>
<td>16218</td>
<td>0.165</td>
<td>2.33*10^{-7}</td>
</tr>
<tr>
<td>4</td>
<td>17909</td>
<td>0.165</td>
<td>2.11*10^{-7}</td>
</tr>
</tbody>
</table>
The lower the thermal diffusivity, the lower the exchange of heat between the outside and inside of the building, the better the thermal insulation. We can see that the thermal diffusivity confirms the results of the first experiment as the sample 4 is the best insulator, while the other are in the same order.

D. Specific Heat Capacity:

I calculated the specific heat capacity of each mixture using the equation which includes the density, the thermal conductivity, and the thermal diffusivity. Table 6 represents the results:

<table>
<thead>
<tr>
<th>Samples</th>
<th>Specific Heat Capacity (J/Kg.K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1442.04</td>
</tr>
<tr>
<td>2</td>
<td>1342.27</td>
</tr>
<tr>
<td>3</td>
<td>497.68</td>
</tr>
<tr>
<td>4</td>
<td>156.39</td>
</tr>
</tbody>
</table>

The sample which requires the highest amount of heat to raise its temperature by 1k is the sample 1 which contains 2% straw and 98% clay. It is followed by sample 2, then sample 3. As for the one requiring the lowest amount of heat is the sample 4.
E. Thermal Effusivity:

The final thermal property is calculated using the other thermal properties. The results are the following:

\[
\begin{array}{|c|c|}
\hline
\text{Samples} & \text{Thermal Effusivity} \\
& (W s^{0.5} m^{-2} K^{-1}) \\
\hline
1 & 1427.39 \\
2 & 1233.16 \\
3 & 414.34 \\
4 & 87.08 \\
\hline
\end{array}
\]

Table 7: Thermal Effusivity of the Samples

In terms of thermal effusivity, the lower its value, the better is the thermal insulation of the sample. The sample with the lowest thermal effusivity is the sample 4 with \(87.08 W s^{0.5} m^{-2} K^{-1}\), making the best sample in terms of thermal properties. The second best is the sample 3.

F. Compressive Strength:

In order to measure the compressive strength of each mixture, I conducted a compressive strength test. The results were the following:
<table>
<thead>
<tr>
<th>Sample</th>
<th>Break Load (Kg)</th>
<th>Area ($m^2$)</th>
<th>Compressive Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>103677.60</td>
<td>0.06435</td>
<td>15.8</td>
</tr>
<tr>
<td>2</td>
<td>100396.67</td>
<td>0.06435</td>
<td>15.3</td>
</tr>
<tr>
<td>3</td>
<td>89897.67</td>
<td>0.06435</td>
<td>13.7</td>
</tr>
<tr>
<td>4</td>
<td>29528.4</td>
<td>0.06435</td>
<td>4.5</td>
</tr>
</tbody>
</table>

As we can see, the samples 1, 2, and 3 all meet the recommended 10Mpa by the European norms. However the sample 4, which has the best thermal properties does not even reach half the recommended compressive strength, which means that using it in building, even for ground level only buildings, can be dangerous.
Simulation

For the simulation, I made a 10m*20m model house using DesignBuilder. The software helped me calculate the heat losses in houses made with the different samples. I also calculated the heat loss for a house built using regular concrete blocks which is used heavily in Guigou as a reference. The heat loss simulation were made using the same thickness (0.165m) for all models. It was also made for a regular winter day.

Figure 29: The Model House Plan
I created models for my samples in DesignBuilder. In order to do so, I had to input the thermal conductivity, the density, the specific heat capacity, and the thickness of each of the samples.
Results and Discussion

In order to make the simulation the most relevant to my study, I set the ceilings, glazing, ground floors, partitions, and external infiltration and ventilation factors to standards as to make the heat loss through the walls most noticeable. The results (see appendix) can be stated as follows:

-The cement brick model:

This model, which is considered as a reference, resulted in 6.77KW/day in heat losses through the walls.

-Sample 1:

The resulted heat loss through the walls for this sample was 4.52KW/day, which is not so different from the reference, meaning that there is no cut back on heat losses using this sample.

-Sample 2:

As for the sample 2, it resulted in a heat loss through the walls equal to 3.92KW/day, which significantly lower than the one from the reference. In order to make sure that these were correct, I ran the simulation again to make sure and it yielded the same results.

-Sample 3:

The sample 3 yielded 1.71KW/day, which is better than the sample 2 and sample 1, which confirms the results of the experimental part.

-Sample 4:

As for the sample 4, it resulted in heat loss through the walls lower than that of sample 3, which was equal to 1.38KW/Day. It is the lowest one among the four samples.
According to the simulation the best sample in terms of thermal efficiency is the sample 4, which yielded in the lowest heat losses through the wall. It was followed by sample 3. As for the sample 1 and sample 2, they showed results lower than the reference meaning that they are not better thermal insulator than sample 4 and sample 3.

As sample 4 does not meet the requirements in terms of compressive strength. The recommended bricks for the village of Guigou is the sample with 92% clay and 8% straw. It showed great thermal insulation in both the experimental study and the simulation. In addition to being strong enough to be used in buildings, it is a cheap and easy to make materials.
Conclusion

As stated before, the goal behind this project is to find a thermo-efficient and cheap building material, for the people of Guigou. For this purpose, I first conducted research on the subject to gather enough information about the building materials, the insulation materials, and their thermal and mechanical properties. Second, I conducted experiment to measure the properties of the chosen materials, which are clay and straw, which proved to be cheap and have a good thermal insulation. I built four samples in order to conduct this part of the study. According to the experimental study, the sample that proven to have the best thermal insulation while having a good compressive strength was Sample 3, which is made of 92% clay and 8% straw. Third, I run a simulation in DesignBuilder for a model house, which was created then run for the four mixtures, in addition to a reference concrete blocks building. The simulation confirmed the results of the experimental study. Therefore, the final result is that the most thermo-efficient building material is a block made of 92% clay and 8% straw.
References


Appendix

DesignBuilder Graphs:

Concrete Blocks:

Sample 1:
Sample 2:

![Graph](image1)

Sample 3:

![Graph](image2)
Sample 4: