School of Science and Engineering

Capstone Report

“Clay Housing in Ben Smim: Modeling Thermal and Mechanical Properties of Clay and Clay Composites”

Al Akhawayn University

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by

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Supervised by

Dr. Asmae Khaledoune
Acknowledgement:

It is not possible to prepare a project report without the assistance and encouragement of other people. This one is certainly no exception.

On the very outset of this report, I would like to extend my sincere and heartfelt obligation towards all the persons who helped me in this endeavor. Without their active guidance, help, cooperation and encouragement, I would not have made headway in the project.

I am ineffably indebted to my supervisor, DR. ASMAE KHALDOUNE for her conscientious guidance and encouragement to accomplish this assignment.

I extend my gratitude to AL AKHAWAYN UNIVERSITY and for giving me this opportunity.

I also acknowledge with a deep sense of reverence, my gratitude towards my parents and members of my family, who always supported me morally as well as economically.

At last but not least, gratitude goes to all my friends who directly or indirectly helped me to complete this project report.

Any omission in this brief acknowledgement does not mean lack of gratitude.

Thanking you,

AFAF ZARKIK
## Contents:

Acknowledgement ............................................................................................................. 1
Abstract .............................................................................................................................. 3
Introduction ......................................................................................................................... 4
Project justification ............................................................................................................ 5
STEEPLE analysis ............................................................................................................... 6
Methodology ....................................................................................................................... 7
Expected Results ............................................................................................................... 7
1. Heat flow modes .......................................................................................................... 8
2. Thermal properties ...................................................................................................... 10
3. Mechanical properties: Compressive strength ............................................................ 12
4. Properties of the clay extracted from Ben Smime ......................................................... 13
   4.1. X-Ray diffraction and chemical composition .......................................................... 13
5. Models of some important features of clay .................................................................. 17
   5.1. Porosity .................................................................................................................... 17
   5.2. Grain Size ............................................................................................................... 22
   5.3. Water content ....................................................................................................... 28
6. Composites .................................................................................................................... 32
   6.1. Types of composites .............................................................................................. 32
   6.2. Description of additives ......................................................................................... 32
7. Models of thermal properties of composites ............................................................... 35
   7.1. Particulate composites ........................................................................................... 35
      7.1.1 Thermal conductivity ....................................................................................... 35
         7.1.1.1. Series model ............................................................................................. 35
         7.1.1.2. Parallel model ........................................................................................ 35
         7.1.1.3. Maxwell’s model ...................................................................................... 35
         7.1.1.4. Hamilton’s model ................................................................................... 36
         7.1.1.5. W.G.M. model ....................................................................................... 36
      7.1.2. Specific heat capacity ..................................................................................... 36
      7.1.3. Thermal diffusivity ......................................................................................... 36
      7.1.2. Thermal effusivity .......................................................................................... 37
      7.2. Fiber reinforced composites .............................................................................. 37
         7.2.1. Rule of mixture ............................................................................................ 37
8. Comparison between the models and the experimental values .................................... 38
9. Discussion ...................................................................................................................... 42
Conclusion ......................................................................................................................... 43
References ......................................................................................................................... 44
Definitions ........................................................................................................................ 46
**Abstract:**

This project is a continuation of Dr. Khaldoune’s work towards providing comfortable living situations to the inhabitants of the village of Ben Smime. This village is set in the outskirts of the city of Ifrane, and is depicted with a very harsh weather during fall and winter, and its population have medium to low income and thus cannot afford heating.

This project aims at developing houses using local, low embodied energy construction materials such as clay, which represents an essential step towards making houses more cost and energy efficient.

While other contributors to this project have mostly focused on performing experiments to test the mechanical and thermal properties of the unfired clay bricks (the primary building material of the Ben Smim project), my contribution will be to find models that not only predict but also explain those thermal and mechanical properties.

In order to achieve such goals, first a study of this clay will be conducted in order to identify the type of clay found in Ben Smim and its characteristics. Afterwards, a series of models will be developed to account for the mechanical and thermal impacts associated with various physical characteristics of the clay namely its grain size, porosity and water content. During each stage a recommendation will be given to improve the quality of the clay so that it becomes a better thermal insulator. Part of the recommendations will be supplementing the clay with natural and sustainable additives also found locally such as sheep wool and other materials that will be used in small percentages such as limestone powder and cement. As part of this project, the thermal properties of the composite of clay and additives will also be predicted using some models and finally these models will be compared with the experimental data (when available) and with literature finding if the experiment could not be performed.
Introduction:

Ben Smim is a small village in the province of Ifrane; it is about 14km from the city. Depicted with the harsh weather of the Atlas Mountains, this remote and economically straggling region is in desperate need of economic housing with good thermal properties.

The new thermal regulation in buildings in Morocco stated by the Moroccan Ministry “Ministère des mines et de l’environnement” made by ADEREE (Agence National pour Le Développement des Energies Renouvelables et de l’Efficacité Energétique) set the standards that should be used in buildings for thermal comfort and optimal energy efficiency. The application of these regulations will be mandatory in one or two years.

This project will seek to exploit the natural thermal properties of clay to create an energy efficient house. Energy efficiency is a modern concept that is based on the simple principle that building materials can provide the necessary insulation and air sealing.

Given the scarcity of energy, and the low to moderate income of most of the inhabitants of the region of Bensmim, the application of clay-based houses, is an excellent alternative for the expensive fired bricks and cement. This application adds little to no cost when initially included in the building process of homes; yet has the effect of realizing a great reduction in operational (energy supply for heat) and non-operational (cost of building material and personal) costs [1].

Given the impact of energy efficient homes on the comfort and well being of present and future generations of Ben Smim, and possibly all other areas of Morocco facing the same issue, it is important to carry scientific research to backup and explain the experiments already performed by other contributors to this project, and as such, this project will help explain the impact of various physical properties of clay such as the grain size, porosity and water content on the performance of our clay both as a building material and as a thermal insulator, and identify and eliminate the weaknesses of our clay. One of the most important contributions of his project will also be to find models to predict thermal conductivity of composites, since they crucial aspect of this project (we will be using mostly local additives to enhance the thermal and mechanical properties of our clay).

A bibliographic study is performed to analyze the state of the art research in this field to acquire a full understanding of construction materials, ceramics and thermal properties of materials, furthermore previous capstones and masters that cover this topic were also be reviewed.
**Project justification:**

In order to emphasize the need to pursue this project, we used the “4 U” method that is based on four factors: Urgent, Unique, Ultra-specific, and Useful.

- **Urgent:**
  
The urgency of this project surges from the new thermal regulations in buildings that were introduced by the Department of Mines and the environment suggested by ADEREE (Agence Nationale pour le Développement des Energies Renouvelables et l’Efficacité Energétique). These regulations which are expected to become mandatory in one or two years, will set the standards of building materials and procedures that will provide thermal comfort and optimal energy efficiency in Morocco, as the standards set by ADEREE will have to be implemented soon, the need for our passive heating housing that ensures energy efficiency will rise. Furthermore, the bad weather conditions that affect the inhabitants of Ben Smime, and the commitment of Al Akhawayn University to help the community in the region of Ifrane also played a crucial role in the urgency of this matter.

- **Unique:**
  
Although clay housing has been historically used to ensure thermal comfort inside houses in dry and hot weather conditions. Nationally wise, this is the first time a real scientific investigation has been launched to ensure that clay housing may have a promising future in passive thermal heating in wet and cold regions of Morocco.

- **Ultra-specific**
  
The project aims at identifying models to predict thermal and mechanical properties of the clay found in Ben Smime. A comparative study of the results found using those models with the experimental data will be carried through. Afterwards a consumption comparison will be established between the thermal conditions of a house built with cement (the most commonly used building material in Morocco) and pure clay. This will allow us to detect the most thermally viable alternative (the one that has the best insulation).

  Finally, a study of the savings that will be attained will allow us to detect which of three construction materials is the most economic.

- **Useful**
A STEEPLE analysis follows to describe the influence of this project on many levels: Societal, technological, ecological, political, legal and ethical level.

**Steeple analysis:**

<table>
<thead>
<tr>
<th><strong>SOCIETAL</strong></th>
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<tbody>
<tr>
<td>Provide comfortable ambient temperature in-doors in a poor region known for it cold harsh weather during winter using local, thermally insulating and sustainable materials.</td>
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<table>
<thead>
<tr>
<th><strong>TECHNOLOGICAL</strong></th>
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<tr>
<td>Using the software Design builder</td>
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<tr>
<th><strong>ECOLOGICAL</strong></th>
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<tbody>
<tr>
<td>- Using sustainable materials found locally instead of the industrialized building materials that generate harmful by-products during the production phase. (Green house gases, water waste etc.)</td>
<td></td>
</tr>
<tr>
<td>- Reduce energy consumption by the residents and by the plants producing fired bricks and cement.</td>
<td></td>
</tr>
<tr>
<td>- Use recyclable, biodegradable and sustainable materials.</td>
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<tr>
<th><strong>ECONOMICAL</strong></th>
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<tr>
<td>- Provide a cheap alternative for cement with better thermal properties.</td>
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<td>- Reduce heating costs.</td>
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<tr>
<th><strong>POLITICAL</strong></th>
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<tr>
<td>Join the Moroccan quest for reducing energy waste.</td>
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<th><strong>LEGAL</strong></th>
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<tr>
<td>This project is compliant with the Moroccan law 47 – 09 introduced in 2009. This law aims to set standards for building in terms of thermal efficiency by setting the frame for the Moroccan thermal regulation project.</td>
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<tr>
<th><strong>ETHICAL</strong></th>
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<td>This project was done for the purpose of helping individuals in critical situations.</td>
<td></td>
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</table>

**Table 1: STEEPLE analysis**
Methodology:
The adopted methodology goes as follows: First, we are going to identify all the thermal and mechanical properties that could influence the quality of our clay houses, mostly thermal conductivity and compressive strength, afterwards, we are going to model these two properties and others if possible based on the most important and imposing characteristics of clay namely porosity, grain size and water content. After studying these features, some recommendations will be suggested to improve the structure of our material in order to be compatible with our needs. These suggestions will most likely involve adding additives such as cement, lime and sheep wool, which means that we will have to study how these materials will affect the ultimate goal of this whole research which is providing comfortable ambient temperature inside clay housing. The mathematical models will be compared to the experimental results found both in Dr. Khaldoune’s research and in similar research to understand and give the right interpretation of the experimental data and propose more experiments to understand and improve the quality of the unfired clay bricks.

Expected Results:
The contribution of this project to Dr. Khaldoune’s ongoing research about this topic will be:

• First, investigate the properties of Ben Smim Clay.
• Second, find many models that will be used to predict thermal and mechanical properties of Ben Smim Clay based on its structure (porosity, gran size and moisture content)
• Third, model the impact of additives on the thermal conductivity and compressive strength of clay.
• Fourth, compare these results with the experimental values.
• Finally, compare costs of using clay as a primary building material as opposed to cement.
1. Heat flow modes:
The end output of this research is to produce a thermally insulating construction material that will retain heat during the winter.
The fundamental modes of heat transfer are:

**1.1. Radiation:**
Since we are referring to a passive solar heating system, the very least of the assumptions is to say that our system absorbs heat from the sun. Heat is transferred from the sun by Radiation, which refers to physical transfer of photons. The radiation emitted by a real surface can be expressed by the Stephan-Boltzmann formula:

\[ Q = \epsilon \sigma A T^4 \]

Where \( \epsilon \) is the emissivity of the surface and it describes how closely a surface can emit radiation energy compared to a black body (Blackbody radiation represents the maximum heat energy a body can emit in an ideal situation its \( \epsilon = 1. \))
Furthermore, a surface can absorb radiation as well and it is a fraction of the energy incident on that surface:

\[ Q_a = \alpha_a Q_l \]

Where \( Q_l \) is the total radiation energy incident on a surface (or irradiation) and \( \alpha_a \) is the absorptivity, which is a dimensionless radiation property of a surface that ranges from 0 to 1 and describes the fraction of energy incident on a surface that is absorbed.

Therefore, the total radiation energy incident on a surface can be expressed as follows:

\[ Q_l = Q_a + Q_r + Q_t = \alpha_a Q_l + \alpha_r Q_l + \alpha_t Q_l \]

Where: \( \alpha_a \), \( \alpha_r \) and \( \alpha_t \) are respectively the absorptivity, reflectivity and transmissivity whose values range from 0 to 1. Predictably, the sum of the absorptivity, reflectivity and transmissivity is 1.
1.2. Conduction:

Conduction is heat transfer that occurs due to random molecular motion or diffusion in the absence of any kind of flow or velocity gradient (translation, rotation or vibration of the molecules). Unlike radiation that can take place in empty space, conduction can only occur at the presence of a medium. Conduction is the primary heat transfer mode in solids and the vibration of molecules in the lattice causes it.

Fourier’s law governs the rate of heat transfer by conduction:

\[ Q = -kA \frac{dT}{dx} \]

\( k \) is the thermal conductivity and it is an extremely important thermal property that we will be using intensively during this project. It describes the ability of a material to conduct heat. \( A \) is the total surface area and \( \frac{dT}{dx} \) is the temperature gradient.
2. Thermal properties

Heat flow mode is only the first step of our research, next come the thermal properties and their contribution.

For the purpose of representing all the entities that contribute to the thermal characterization of our composite (clay and additives), we will focus on the U-value that describes the thermal insulation of the building based on the materials used, along with the “dynamic” thermo-physical parameters that are both unique to each material and are related among them, which are:

- Thermal conductivity $k$ (J.m$^{-1}$K$^{-1}$).
- Thermal diffusivity $\alpha$ (m$^2$. S$^{-1}$)
- Thermal effusivity $\varepsilon$ (J/m.s$^{1/2}$.K)

They are related among each other with the equation: $\varepsilon = \frac{\lambda}{\alpha^{1/2}}$. Therefore calculating two parameters will yield to the third.

2.1. Thermal conductivity:

As mentioned earlier, thermal conductivity describes the ability of a material to conduct heat and its unit is [J/m. K]. High thermal conductivity allows the material to transmit heat quickly when subjected to a small temperature gradient. Since the goal is to create thermal insulation, we want thermal conductivity to be as low as possible. [5]

Thermal conductivity is associated with heat transfer through conduction, meaning through the collision of molecules (vibration, translation, rotation). Therefore, the higher the density of the material, the more conductive it is [5], so we want our material lighter.

Thermal conductivity allows for the transfer of heat from a warm surface to a cooler one, therefore lowering the temperature of the surface that emits heat. The temperature of the surface is only lowered by a quantity that depends on its heat capacity. And this heat transfer allows low temperature to infiltrate the house. [5]

It is now imperative to define heat capacity. Specific heat capacity $C_p$ is the increase in internal energy associated with a rise in temperature, in other words, the material’s capacity to store heat. It can also be defined as the amount of heat per unit mass required to raise the temperature by one degree Celsius.

Volumetric heat capacity $\rho_c$ is the product of density and specific heat capacity.
Materials have different heat capacities because they have different ways of storing heat, as we said earlier, heat storage which is related to the quantity of heat flow can be under the form of vibration, translation or rotation of the molecules.

⇒ Since our goal is to thermally insulate our house from the cold, we need our energy efficient home to have a very low thermal conductivity.

2.2. Thermal diffusivity:
Thermal diffusivity measures the time it takes for a volume of material to become thermally equilibrated with its surrounding. It is calculated using the formula:

\[
\alpha = \frac{k}{\rho C_p}
\]

One can notice that thermal diffusivity increases with increasing thermal conductivity and decreases with increasing heat capacity.

Therefore, thermal diffusivity is a measure of a thermal penetration depth through a material’s wall in a given environment. [5]

Consequently, a material with high thermal diffusivity stays close to thermal equilibrium with its surrounding and stores little energy, conversely, a material with low thermal diffusivity takes will ever slowly return energy stored energy to its environment. [5]

⇒ We want our clay walls to store a large amount of energy and not let it infiltrate the inside of the building; therefore, we want our house to have low thermal diffusivity.

2.3. Thermal effusivity:
Thermal effusivity describes the quantity of energy exchanged across a mass surface, its unit of measurement is [J/m.s^{1/2}.K]. It is calculated using either formula:

\[
\varepsilon = \frac{k}{\sqrt{\alpha}} \quad \text{Or} \quad \varepsilon = \sqrt{\frac{k p C_p}{}}
\]

If a material must experiment high heat flux across its surface during equilibration with its surrounding of a different temperature, it is said to have a high thermal effusivity.

The influence of thermal effusivity is analogous to the effect of mechanical inertia, to what it owes its nickname: the thermal inertia. To further explain, mechanical inertia is the magnitude of the force required to change an object’s position, and thermal effusivity, i.e. “thermal inertia” is the magnitude of the energy required to cross a surface of a given width. [5]
3. Mechanical properties: compressive strength

Compressive strength is the ability or capacity of a material to withstand loads under compression, which tend to reduce the size of the material. Materials fracture at their compressive strength limit called the ultimate compressive strength, or yield compressive strength.

The compressive strength is obtained experimentally using a compressive stress test. The apparatus used for this test applies a uniaxial compressive load to the material until it fractures, thus defining its yield strength. The specimen is shortened and spread by the load applied, simultaneously a stress-stress curve is plotted by the instrument.

It is important to study the compressive strength of our clay since it will be used as a building material under the form of unfired bricks, meaning our clay has to withstand the load of the entire building. This clay needs to abide to national standards of compressive strength of building materials.

Ceramics are known for having excellent compressive strength, which makes them a good building material. Figure 4 shows how ceramics, and thus clay, have excellent compressive strength.

![Figure 2: Compressive strength of ceramics and other materials](image)

Figure 2: Compressive strength of ceramics and other materials [18]
4. Properties of Clay Extracted Ben Smim:

4.1. X-ray diffraction and chemical formula:

The X-ray diffraction technique was used to determine the chemical composition of the sample clay obtained from Ben Smim. After analyzing the sample clay using this technique, the results showed that the clay was composed of Mica (K, Mg, Fe, Al) which is a mineral mixture, Quartz (SiO$_2$), and Alumina (Al$_2$O$_3$).

The noticeable percentage of Illite, which exceeded 80% and the minor presence of Kaolin, lead to the conclusion that the soil in Ben Smime is mostly Illite. Illite clay has many advantages making it potentially a good construction material, for example:

- Low water absorption (the voids between the tetrahedral and octahedral sheets are fixed by the potassium ions K$^+$ that prevents the swelling of the clay by infiltration of the water between its sheets.)
- Low shrinkage.
- Low plasticity.

Below is the X-Ray diffraction pattern of a sample Clay from Ben Smime and those of pure Illite and Kaolin soil:

![X-ray diffractometer spectrum of the clay sample extracted from Bensmime](image)

Figure 3: X ray diffractometer spectrum of the clay sample extracted from Bensmime
Illite is a clay-sized micaceous mineral that has the property of being non-expanding. Its microstructure is constituted by the repetition of tetrahedron – octahedron – tetrahedron (TOT) layers. The space in the interlayers is mostly occupied by hydrated potassium cations that account for the absence of swelling. These properties allow illite clay to have a major use in the ceramics and clay brick industry.
Illite clay in general is: hard, chemically stable, wear resistant, brittle, thermally and electrically insulating, non-expending, swelling resistant, oxidation resistant, prone to thermal shock, has low tensile strength and high compressive strength.

Figure 6: Crystalline structure of Illite clay [16]

In this project we seek to exploit the strengths of the clay and improve its weaknesses in order to come up with an adequate building material with good thermal and mechanical properties.

Figure 7: Clay powder sample

Experimental measurements reveal the following thermal and physical parameters of the clay:

- Thermal conductivity: \( k = 0.92 \text{ W/ m. K} \)

- Specific heat: \( C_p = 907.7 \text{ J/ kg. K} \)
- Density: $\rho = 1870.36 \text{ Kg/m}^3$

Using fluorescence X method, the chemical composition of the sample clay was found, table 2 summarizes each chemical element and its percentage.

**Table 2: Chemical composition of the clay [1]**

<table>
<thead>
<tr>
<th>Chemical Element</th>
<th>Percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO$_2$</td>
<td>59.2</td>
</tr>
<tr>
<td>Al$_2$O$_3$</td>
<td>22.4</td>
</tr>
<tr>
<td>Fe$_2$O$_3$</td>
<td>6.69</td>
</tr>
<tr>
<td>CaO</td>
<td>0.0777</td>
</tr>
<tr>
<td>MgO</td>
<td>0.97</td>
</tr>
<tr>
<td>K$_2$O</td>
<td>2.53</td>
</tr>
<tr>
<td>TiO$_2$</td>
<td>0.832</td>
</tr>
<tr>
<td>PO</td>
<td>0.458</td>
</tr>
<tr>
<td>P.a.f</td>
<td>5.34</td>
</tr>
</tbody>
</table>

The chemical formula is given as $(\text{K,H}_3\text{O})(\text{Al,Mg,Fe})_2(\text{Si,Al})_4\text{O}_{10}[(\text{OH})_2,\text{(H}_2\text{O})]$.

- The presence of silica (SiO$_2$) in abundance in our clay is a good indicator of its thermal properties. Silica is the mostly widely used ceramic material and it is used for thermal insulation, refractories, abrasives, fiber reinforced composites etc.
- Alumina (Al$_2$O$_3$) is also widely used and it contains molten metal, consequently it has a high melting temperature combined with high strength so it is a valuable element as well.
5. Models of important clay features:

5.1. Porosity:
Porosity represents the most important defect in polycrystalline ceramics such as clay. Porosity confers to clay both positive and negative properties.

- Porosity can be used to manufacture lightweight products, products with good thermal insulation etc.
- Negative aspects include friability, loss of strength, undesirable fluid absorption.

The forming of ceramics from powders necessarily generates porosity by fixing, in 3 dimensions, positions and relationships of inter-particle voids. Low-pressure forming methods generate higher porosity and higher pressures produce less. [7]

The size of the pores depends on:

- The particle size distribution.
- Shape of the starting powders and various additives such as binders and liquids. (Liquids create porosity in the early stages of firing as they escape in the form of gas.)

The graph in figure 9 summarizes the effect of pores on both mechanical properties and thermal properties of clay:

![Figure 8: Effect of porosity on thermal and mechanical properties of clay](image)

Pores may be either interconnected or closed:

- Interconnected pores can be measured by the apparent porosity formula. Apparent porosity relies on water absorption and it is used to determine permeability. It is
calculated by weighing the dry clay ($W_d$), then reweighing the ceramic both when it is suspended in water ($W_s$) and after it is removed from water ($W_w$).

- True porosity includes both interconnected and closed pores. It is related to the properties of the clay.

Below are the formulas of the apparent and true porosity:

\[
\text{Apparent Porosity} = \frac{W_w - W_d}{W_w - W_s} \times 100 \tag{1}
\]

\[
\text{True porosity} = \frac{\rho - B}{\rho} \times 100 \tag{2}
\]

We are only interested in true porosity in the next sections.

Bulk density of our clay is between 1600 and 1700 Kg/m$^3$ therefore, its true porosity ranges from 9.1% to 14.4%

### 5.1.1. Compressive strength:

Quite a few models have been developed to study the effect of porosity on the tensile strength. Bellow are some of these models that predict the tensile strength of materials based on their apparent porosity:

Balshin obtained the following model for his study of metal ceramics:

\[
\sigma = \sigma_0 (1 - p)^b \tag{3}
\]

Where $\sigma$ is the strength, and $\sigma_0$ is the strength at zero porosity, $p$ is the porosity and $b$ is an empirical constant. [17]

Ryshkewitch from a study of compressive strength of Al$_2$O$_3$ and ZrO$_2$:

\[
\sigma = \sigma_0 e^{-kp} \tag{4}
\]

Such that $k$ is an empirical constant. [17]

Schiller, on the basis of the study of set sulfate plasters, proposed the relation:

\[
\sigma = n \ln \left( \frac{P_0}{p} \right) \tag{5}
\]

Such that $n$ is an empirical constant.

Hasselman suggested the equation of a linear relationship between strength and porosity for different refractory materials:

\[
\sigma = \sigma_0 - cp \tag{6}
\]

Such that $c$ is an empirical constant. [17]
All the equations above suggest that the compressive strength decreases as porosity increases. Therefore, we need to suggest a way to decrease porosity so that the unfired clay bricks may have an adequate compressive strength.

**Recommendation:**
We suggest adding sheep wool to the clay in order to reduce the porosity of the unfired clay bricks. The wool fiber will reduce porosity by filling the gaps or the pores and decrease the size of the starting powder.

**5.1.2. Thermal conductivity:**
Thermal conductivity through a solid is controlled largely by phonon transport. The definition of phonons explicitly mentions that the presence of point or extended defects dramatically reduces thermal conductivity.

Pores act as major disruptions to the crystal lattice (i.e., are large defects) and thus have a strong effect on thermal conductivity. When defects are present in a solid, the thermal conductivity is given by:

\[ k_p = k_i - \delta k_p \]  \hspace{1cm} (7)

Where \( k_p \) is the phonon conductivity, \( k_i \) is the intrinsic conductivity and \( \delta k_p \) is the decrease in conductivity that results from phonon scattering by the defects. [16] The thermal conductivity is reduced because of a decreased mean free path for phonon transport as a result of phonon scattering at pores. The mean path is the average distance travelled by the phonon before scattering, the latter can be caused by defects, boundaries or other phonons.

In the first successful model for thermal conductivity, Debye used an analogy of the kinetic theory of gases to derive an expression for the thermal conductivity in solid materials:

\[ k = \frac{1}{3} C \nu \lambda_p \]  \hspace{1cm} (8)

Where \( C \) is the specific heat of the material (clay in this case), \( \nu \) is the speed of sound in the object and \( \lambda_p \) is the phonon mean free path, which is the distance between phonon scattering centers.

From the above equation, if the mean free path is decreased, the thermal conductivity can also be seen to decrease. Together equations 8 and 9 explain why the thermal conductivity of the highly porous materials is less than less porous ones.

Figure 10 illustrates phonon scattering due to their collision with pores:
The thermal conductivity of a porous material is strongly dependent of the material density (or fraction of pores). According to C. Effting, S. Güths et al., thermal conductivity of porous ceramics is well correlated with the porosity as shown by the equation bellow:

\[
\frac{k}{k_0} = \frac{1-P}{1+nP^2}
\]  

(9)

Such that \(k\) is the thermal conductivity of a porous ceramic, \(k_0\) is the thermal conductivity of a pore free ceramic, \(P\) is the porosity of the ceramic and \(n\) is an empirical constant. [16]

Equation 10 shows that heat conductivity decreases as \(p\) increases.

5.1.3. Thermal Effusivity:

According to C. Effting, S. Güths et al., a model predicting thermal effusivity can be derived from equation 10. As mentioned before, thermal effusivity (thermal inertia) describes the quantity of energy exchanged across a mass surface, its unit of measurement is [J/m.s\(^{1/2}\).K]. It is calculated using the formula: \(\varepsilon = \sqrt{k\rho C_p}\). Thermal effusivity was modeled by the following equation:

\[
\frac{\varepsilon}{\varepsilon_0} = \frac{1-P}{\sqrt{1-nP^2}}
\]  

(10)

Such that \(\varepsilon\) is the thermal effusivity of a porous ceramic, \(\varepsilon_0\) is the thermal conductivity of a pore free ceramic, \(P\) is the porosity of the clay and \(n\) is an empirical constant. [16]
5.2. **Grain size:**

The properties of polycrystalline materials depend on the content of planar defects, meaning grain boundaries that are the product of grain size. Typically ceramics with a small grain size are stronger than coarse-grained ceramics [8]. Figure 11 summarizes the effect of grain size on both mechanical properties and thermal properties of clay:

![Diagram](Figure 10: Effect of grain size on thermal and mechanical properties of clay)

5.2.1. **Compressive strength:**

Basically, the compressive strength of polycrystalline materials is negatively proportional to its grain size. The more our clay is fine-grained the better strength it has.

The Hall-Petch effect is a way to quantify the trend of increasing strength with decreasing grain size. [10] The variation of compressive strength depending on grain size can be expressed using a power-law formula:

\[
\sigma_y = \sigma_0 + kd^{-1/2}
\]

(11)

Where:

- \(\sigma_y\): Yield strength
- \(\sigma_0\): Friction stress
- \(k\): The Hall-Petch constant
- \(d\): Diameter of the grain
The principle behind the impact of grain size on the strength is that dislocations are forced to pile up in at the grain boundaries. Figure 8 illustrates the Hall-Petch effect. As we apply a friction stress to grain 1, we can see that the grain is favorably oriented for slip. However, macroscopic flow requires dislocation activity in all grains (grain 2), and this may be induced by the internal stress caused by the dislocation pile-up at the grain boundaries of grain 1. This stress may cause dislocation emission from the boundary or may activate a dislocation source (r). [10]

The magnitude of the stress concentration depends on the number of dislocations in the pile-up and increases with diameter d.

![Figure 11: Dislocation pile-up at the grain boundaries](image)

The Hall-Petch constant is a material property and it can be calculated using:

\[ k = \sqrt{\frac{4\ G\ b\ \tau_c}{\pi}} \]  \hspace{1cm} (12)

Grain size distribution is found experimentally using sieving. The sample is weighed before and after being dried so that water content is determined. Afterwards, the sample will be soaked again and washed through a sieve that has wholes of 80µm and the leftover content of the sieve, called the “refusal”, is then dried and measured. A series of sieves are placed one on top of the other to separate grains of the clay depending on their size.
Table 5 summarizes the clay particle size distribution:

Table 3: Percentages of grain sizes in the clay

<table>
<thead>
<tr>
<th>Type of grains</th>
<th>Size of grains</th>
<th>Percentage in the sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fine grains</td>
<td>0.08 → 0.315 mm</td>
<td>92%</td>
</tr>
<tr>
<td>Medium grains</td>
<td>0.315 → 1.25 mm</td>
<td>7.84%</td>
</tr>
<tr>
<td>Large grains</td>
<td>1.25 → 6.3 mm</td>
<td>0.16%</td>
</tr>
</tbody>
</table>

Recommendation:

Strong materials are generated by particles the size of microns, therefore we suggest reducing the grain size of Ben Smim clay to microns using ball milling.

Figure 12: Sieves used for the particle size analysis.

Figure 13: Ball mill
5.2.2. Creep:

One of the most important mechanical properties of building materials is their resistance to creep. It is important to mention that creep is highly sensitive to temperature since thermal activation makes the largest contribution to plastic flow when stress is not high enough to cause it.

There are many creep mechanisms as illustrated in figure 15:

![Figure 14: Creep mechanisms](image)

We are particularly interested in types of creep that are related to the grain size and therefore, to the mass of the grains. These creep mechanisms are caused by stress related to shifting of the mass by gravity specially around the particle boundaries.

Grain size dependent creep mechanisms are: Nabarro-Herring creep and Coble creep.

- Nabarro-Herring creep is defined as creep that occurs by mass transfer, meaning the diffusion of atoms from regions of lower algebraic stress to higher stress. [10]
- Coble creep also occurs by mass transfer, but along interfaces, such as grain boundaries.

We will only consider Nabarro-Herring creep because Coble creep may be caused by other interfaces.

The Nabarro-Herring creep as mentioned earlier arises from mass transfer. This mass transfer is the product of diffusion to/from the grain boundaries through the bulk lattice. [10]

The Nabarro-Creep dependence on grain size is expressed in the following formula:

$$\dot{\varepsilon} = A_{NH} \left(\frac{D_{Bulk}}{d^2}\right) \left(\frac{\sigma \Omega}{kT}\right)$$

(13)

Where:

- $\dot{\varepsilon}$ the rate of change of strain.
- $A_{NH}$ is the activation energy which is equal to enthalpy.
- $D$ is the diffusion coefficient of the material.
• \( T \) is the temperature.
• \( \Omega \) is the atomic volume.
• \( \sigma \) is the stress.

From the Nabarro-Herring creep equation; we can see that larger grain sizes provide more resistance to creep. Naturally, the ideal material to resist creep would be a single crystalline material.

*Adolf Fick introduced the diffusion coefficient \( D \) in 1855 as part of Fick’s law of diffusion. Fick’s law of diffusion states that defines the diffusion flux as:

\[
J_v = D \times \frac{dN_v}{dx}
\]  

(14)

Where:

• \( J_v \) is the diffusion flux.
• \( D \) is the diffusion coefficient**.
• \( N_v \) is the concentration of vacancies.
• \( x \) is the distance over which the diffusion occurs which is approximately the grain diameter.

** The diffusion coefficient is such that:

\[
D = \frac{1}{f} \times kT
\]  

(15)

Where \( f \) the friction coefficient is:

\[
f = 6\pi h r
\]  

(16)

Such that:

• \( h \) is the viscosity
• \( r \) is the radius of the sphere (assuming that the shape of the grain is spherical).[10]

**Recommendation:**

We suggest adding Portland cement and powdered limestone (reduced to very fine particles) to fill the voids between the grains, which will stabilize the matrix throughout hinder the diffusion of the clay atoms. (Other experiments have suggested that this approach is successful) [11].

5.2.3. Thermal conductivity/resistivity:

Thermal conductivity is affected by grain size distribution in polycrystalline materials since phonons tend to scatter in granular crystals.
The underlying assumptions of this model are:

- All grains are considered to be uniform ellipsoids with the x and y axis at the direction of a and b.
- P and N denote respectively the previous and next grain.
- I denotes the intensity of the phonon in the grain.
- The grains span by distance D.
- Heat transfer occurs along the direction of z.
- L and J are two subscripts that denote respectively quantities in the grains, and quantities in the grain boundaries.

Unfortunately, aside from the particles in the nano-scale there doesn’t seem to exist a mathematical model that can predict accurately the impact of grain size on thermal conductivity. However, literature strongly suggests that thermal conductivity decreases as grain size increases. Therefore, we suggest an empirical model be found based on our clay.
5.3. Water content:

Moisture content competes with clay content inside the unfired bricks. Since clay bricks are the primary support for our building we want to reduce water content as much as possible. The current percent water content is between 4.5 and 6%.

5.3.1. Compressive strength:

The effect of moisture content on the strength of unfired bricks has been previously reported. Figure 17 describes how moisture content affects the compressive strength of different clay types. It also illustrates that different clay types absorb water at different percentages.

![Figure 16: Effect of moisture content on net compressive strength of different clay types](image)

Figure 16: Effect of moisture content on net compressive strength of different clay types [12]

Figure 17 represents the effect of water content on clay in a purely empirical basis on various types of clay. Table 4 illustrates the results of the Atterberg test performed on these clay samples:

<table>
<thead>
<tr>
<th>Table 4: Results of Atterberg Test of Various clay types</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit code</td>
</tr>
<tr>
<td>-----------</td>
</tr>
<tr>
<td>A</td>
</tr>
<tr>
<td>B1</td>
</tr>
<tr>
<td>B2</td>
</tr>
<tr>
<td>C</td>
</tr>
<tr>
<td>D</td>
</tr>
<tr>
<td>E</td>
</tr>
</tbody>
</table>

Based on previous experiments performed by Dr. Khaldoune’s team, the results of the Atterberg test on our clay are given in table 5:
Table 5: Results of Atterberg Test of Ben Smim clay

<table>
<thead>
<tr>
<th>Liquid Limit</th>
<th>Plastic Limit</th>
<th>Plasticity Index</th>
<th>Net Dry Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>37.5%</td>
<td>22.6%</td>
<td>15</td>
<td>1970 kg/m³</td>
</tr>
</tbody>
</table>

These results are close to the sample E, we can conclude that illite is the clay represented by the letter E and therefore, this experimental data is extremely relevant and can be used in our project. We would like to explore the various factors that influence this effect.

The compaction strength of the unfired brick is naturally related to the confining stress that is applied to it.

![Figure 17: Schematic of confining stress applied to unfired clay brick](image)

The model that we chose was developed by Heath et al. and it assumes that compaction strength is linearly related to the effective confinement stress. This relationship is expressed by the equation:

\[ f_c = K \sigma \]  

(17)

The parameters present in the equation are:

- \( f_c \) is the ultimate compressive strength (any stress unit applies).
- \( K \) is a unit less constant and is equal to: \( K = \frac{2 \sin(\phi)}{1 - \sin(\phi)} \) such that \( \phi \) the effective friction angle for the soil in degrees.
- \( \sigma \) is the effective confining stress, which is the sum of applied confinement stress and confinement from soil suction.

Now, we will express the effective confining stress as a function of water content.

\[ \sigma = cw^c \]  

(18)

Where:

- \( w \) is the gravimetric water content.
- \( c \) is a variable inversely related to grain size. (As the grains become finer, \( c \) increases).
• B is a unitless constant, which describes the reduction in strength with increasing moisture content (i.e. B is negative). [12]

Combining equations 12 and 13 will yield to the following equation, which expresses the compressive strength of clay as a function of water content.

\[ f_c = K c w^B = A w^B \]  \hspace{1cm} (19)

From the equation above we can see that compressive strength has reverse exponential relationship with water content which is what it is illustrated in figure 15.

5.3.2. Thermal conductivity:

According to our extensive research, there doesn’t seem to exist a model that accurately predicts effective thermal conductivity of a material as a function of its moisture content.

However, H. Bal, Y. Jannot et al., considered water as an additive and used the mixture models that will be described in section 8.

In this context, water is treated as an additive and clay as the continuous phase.

The research showed that water content has a strong influence on thermal conductivity.
6. Composites:

Composite materials are multiphase materials obtained by artificial combination of different materials, so as to attain properties, like higher strength, stiffness, fatigue life, less weight, resistance to higher temperatures, which the individual components by themselves cannot attain. The concept of improved performance is broad and includes increased strength or reinforcement of one material by the addition of another material, as well as increased toughness, decreased coefficient of thermal expansion, and decreased thermal conductivity.

One of the most commonly used composite construction material is concrete, which is obtained by combining cement (the matrix), sand (fine aggregate), gravel (coarse aggregate), and other additives known as admixtures may be added (short fibers for example).

6.1. Types of composites:

Figure 21 classifies composites:

![Figure 18: Types of composites](image)

In this project we will focus on particle-reinforced composites, and fiber reinforced composites. The need for additives will be further explained in the following sections.

6.2. Description of the additives:

6.2.1. Portland Cement:

The reaction between the soil and cement will have both long term and short term effect on the unfired clay. The effect of adding the cement is mainly improving both dry and wet compressive strength. However it will have other benefits such as improved wear and erosion resistance, abrasion is also reduced and rain endurance will also be enhanced. The ideal amount of Portland cement to add to the unfired clay bricks is between 3 to 8%, the more the porosity and shrinkage, the more the percentages shifts towards the upper end of the range. [19]
The thermal properties of Portland cement as stored in the Design Builder’s materials database are:
- Thermal conductivity: $k = 0.15 - 0.24$ W/m.K
- Specific heat: $C_p = 1000$ J/kg.K
- Density: $\rho = 1200$ Kg/m3

6.2.2. Lime:
Lime refers to products derived from burnt limestone. Limestone is a naturally occurring and abundant sedimentary rock consisting of high levels of calcium and/or magnesium carbonate, and/or dolomite (calcium and magnesium carbonate), along with small amounts of other minerals. It is extracted from quarries and underground mines. [14]
Adding lime to clay is also effective on both the short and the long term. The short term effect will cause the flocculation of clay which will make the clay more cohesive and on the long term the reaction of lime with carbon dioxide and the pozzolanic reaction between clay and lime. This will make our building material even greener. [19]
The thermal properties of lime as stored in the Design Builder’s materials database are:
- Thermal conductivity: \( k = 0.17 \) W/m.K
- Specific heat: \( C_p = 1090 \) J/kg.K
- Density: \( \rho = 1500 \) Kg/m³

6.2.3. Sheep wool:
The adobe clay will be molded into bricks and then sun-dried, leading to shrinkage and cracking during drying. Therefore, an organic fiber in the form of sheep wool will be added to ensure dimensional stability and strength. Most fiber-reinforced composites provide improved strength, fatigue resistance, Young’s modulus, and strength to weight ratio by incorporating strong, stiff, but brittle fibers into a softer more ductile matrix.

The strength of a composite increases when the aspect ratio is large.

- Making the diameter as small as possible gives the fiber less surface area, and consequently, fewer flaws that might propagate during processing or under load.
- The ends of a fiber carry less of the load than the remainder of the fiber; consequently, the fewer the ends, the higher the load-carrying ability of the fibers.

The benefits of sheep wool are:
- Durability and resilience: Each wool fiber is a molecular coil spring making it remarkably elastic. This flexibility makes the wool fiber durable and resilient. [2]
- Absorbency: wool is a hygroscopic fiber. Wool can absorb up to 30% of its weight in water without feeling damp or clammy. This capacity makes wool a good thermal regulator. [2]
- Resistance to flame: the moisture enrapeted by the wool fiber allows it to be flame resistant.
Similarly, experimental measurements reveal the following thermal and physical parameters of sheep wool:

- Thermal conductivity: \( \lambda = 0.035 \text{ – } 0.042 \text{ W/m. K} \)
- Specific heat: \( C_p = 1700 \text{ J/kg. K} \)
- Density: \( \rho = 10 \text{ - } 30 \text{ Kg/m}^3 \)

7. Models of thermal properties of composites:

7.1. Particulate composites:

7.1.1. Thermal conductivity:

This section of the project describes various models that have been developed by researchers to estimate the thermal conductivity of mixed materials.

According to H. Bal, Y. Janot et al. the series model represents the lower bound of the thermal conductivity and the parallel model represents the upper bound. They will be used to determine the boundaries of the equivalent thermal conductivity values that one can obtain from this mixture.

Such that: \( \lambda_\parallel \leq \lambda \leq \lambda_\|$.

\( y \) represents the mass fraction of the additive in the clay.

7.1.1.1. The series model:

The series model assumes that the dispersed phase is arranged in series with the matrix, therefore, the heat flux hits the surface smoothly without disruptions, yielding to the lowest bound for \( k \).

\[
k_\perp = \frac{1}{\frac{1}{k_{cont}} + \frac{y}{k_{disp}}} \quad (22)
\]

7.1.1.2. The parallel model:

Of similar importance is the thermal conductivity in the principle direction (since this is a 2D model), namely the parallel direction. The parallel model assumes that the dispersed phase and the matrix are connected in parallel. This expression is considered as the upper bound for \( k \).

\[
k_\parallel = (1 - k) \cdot \lambda_{cont} + y \cdot k_{disp} \quad (23)
\]

Such that clay is the continuous phase and sheep wool is the dispersed phase. [6]

7.1.1.3. Maxwell’s model:
Maxwell’s model assumes that the dispersed phase particles are spherical and that there is no contact between them.

\[ k_{eq} = k_{cont} \left[ \frac{2y^{k_{disp}}}{(k_{cont})^{(1-y)}+(1+2y)^{k_{disp}}} \right] \] (24)

7.1.1.4. **Hamilton’s model:**

Hamilton’s model is derived from Maxwell’s model but takes into consideration the random shape of the dispersed particles through the parameter of sphericity \( \xi \).

\[ k_{eq} = k_{cont} \left[ \frac{k_{disp}+(n-1)k_{cont}+(n-1)y(k_{cont}-k_{disp})}{(n-1)k_{cont}+k_{disp}+y(k_{cont}-k_{disp})} \right] \] (25)

Such that \( n = \frac{3}{\xi} \). Note that when \( \xi = 1 \), Hamilton’s model is equivalent to Maxwell’s model. [6]

7.1.1.5. **Weighted geometric mean equation (Woodside and Mesmer’s model):**

\[ k_{eq} = k_{disp}^y \cdot k_{cont}^{(1-y)} \] (26)

7.1.1.6. **Krischer’s model:**

\[ \lambda = \frac{(\lambda_{Series})(\lambda_{//})}{A(\lambda_{Series}) + (1-A)(\lambda_{//})} \] (27)

To apply these models, one needs to know the thermal conductivity of the continuous and dispersed phase that were measured experimentally using the asymmetric or symmetric transient hot plate method. [6]

7.1.2. **Specific heat capacity:**

Experimentally, specific heat capacity can be measured by using a calorimeter that is fundamentally used to measure heat exchange during a reaction.

The mixture’s specific heat capacity is a volume fraction average of the pure materials heat capacities [4]:

\[ C_p = \sum_i Y_i C_{p,i} \] (28)

7.1.3. **Thermal diffusivity:**

Thermal diffusivity describes how long it takes for a material to adapt to the ambient temperature. It is a function of density, conductivity and specific heat capacity:

\[ \alpha = \frac{k}{\rho C_p} \] (29)
Which brings up the following question: how to calculate the density of a composite material?

According to the rule of mixtures, the density of the composite is a weighted average of the density of the matrix and of the dispersed phase:

\[
d_c = d_m V_m + d_f V_f
\]

(30)

Such that:

* \(d_c, d_m\) and \(d_f\) are respectively the density of the composite, the matrix and the dispersed phase.

* \(V_m\) and \(V_f\) are the volume fraction of the matrix and the dispersed phase respectively.

**7.1.4. Thermal effusivity:**

Once the thermal conductivity, the specific heat capacity and the density of the composite are measured, one can calculate the thermal effusivity of the composite using either of these formulas:

\[
\varepsilon = \frac{k}{\sqrt{\alpha}}
\]

(31)

\[
\varepsilon = \sqrt{k\rho C_p}
\]

(32)

**7.1.5. The rule of mixture:**

Density of composites is calculated using the mixture rule:

\[
\rho_c = f_m \rho_m + f_f \rho_f
\]

(33)

Subscripts f and m refer to the matrix and fiber \((f_m = 1 - f_f)\)

In addition, we can also use the mixture rule to make an approximation of thermal properties of clay is going to change when supplemented with additives:

**Table 6:** Impact of additives on thermal properties of clay

<table>
<thead>
<tr>
<th>Sample</th>
<th>Density (kg/m³)</th>
<th>Thermal conductivity (W/m*K)</th>
<th>Thermal diffusivity (m²/s)</th>
<th>Thermal effusivity (W.s⁰.⁷/m²K)</th>
<th>Specific Heat (J.K/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure Clay</td>
<td>1870.36</td>
<td>0.92</td>
<td>5.36*10⁻⁷</td>
<td>1249.76</td>
<td>907.7</td>
</tr>
<tr>
<td>Clay + 3% cement</td>
<td>1665.75</td>
<td>0.88</td>
<td>5.73*10⁻⁷</td>
<td>1162.47</td>
<td>922.1</td>
</tr>
<tr>
<td>Clay + 3% lime</td>
<td>1762.51</td>
<td>0.73</td>
<td>4.35*10⁻⁷</td>
<td>1105.69</td>
<td>950.2</td>
</tr>
<tr>
<td>Clay + 3% Sheep wool</td>
<td>1814.84</td>
<td>0.89</td>
<td>5.26*10⁻⁷</td>
<td>1251.16</td>
<td>931.47</td>
</tr>
<tr>
<td>Clay + all the</td>
<td>1785.23</td>
<td>0.825</td>
<td>5.175</td>
<td>1183.04</td>
<td>936.51</td>
</tr>
</tbody>
</table>

35
The results match our expectations, thermal conductivity decreases significantly as the material gets lighter (decrease in density), thermal effusivity however increases.
8. Comparison between models and experimental results:

Some of the experiments that need to be performed to confirm the results could not be executed due to the lack of time and equipment. Therefore, any experiment that could not have been carried out will be replaced by an experiment found in the literature review. We suggest these same experiments be carried out to confirm the results for Ben Smime clay.

8.1. Porosity:

8.1.1. Compressive strength:

X. Chen, S. Wu and J. Zhou compared the models with the experimental results found; the ceramic material they used was cement mortar. The results showed that the models successfully predicted the compressive and compressive strength of the ceramic material.

![Figure 22: Experimental data and models on compressive strength-porosity dependence. [17]](image)

8.1.2. Thermal conductivity and effusivity:

C. Effting, S. Gütks et al. ran an experiment on a ceramic tile such that n=3 and k_0=1.65W/m.K. The results they found matched the model, therefore, I think we should run an identical experiment to confirm that this model will predict the thermal properties of our clay as well. Figure 26 illustrates that the model does indeed predict the behavior of thermal conductivity and effusivity as a function of porosity.
8.2. Grain size:

8.2.1. Compressive strength:

The Hall-Petch equation clearly states:

$$\sigma_y = \sigma_0 + kd^{-1/2}$$

Therefore:

$$\frac{\sigma_y - \sigma_0}{k} = d^{-1/2}$$

Meaning, as $d^{-1/2}$ increases or as $d$ decreases, the yield strength increases. Figure 27 illustrates this compared with different types of clay the unit of the y-axis is KPa and the unit of the x-axis is $\mu$m$^{-1/2}$:

Figure 23: Measured and theoretical conductivity and effusivity as a function of porosity [16]

Figure 24: The effect of grain size in the strength of different types of clays [10]
8.2.2. **Creep:**
No experimental data was found to back up this model. This may be due to the fact that creep occurs more frequently in metals and polymers therefore a creep test is not suitable for ceramics.

8.2.3. **Thermal conductivity:**
No model was found. However, the literature suggests that thermal conductivity increases with grain size.

8.3. **Water content:**

8.3.1. **Compressive strength:**
Heath, A., Walker, P., Fourie, C. and Lawrence, M. conducted a compressive test produce on different clay types, and they came out with the conclusion that the model successfully predicts compressive strength as a function of water content. However, it also shows that the model deviates at high moisture content. The optimum water content in our clay is about 12.5%, therefore this model may not be representative.

![Figure 25: Model and Experimental effect of water content on compressive strength](image)

8.3.2. **Thermal conductivity:**
Water content has an important influence on thermal conductivity. The most representative models that could predict this influence accurately are: Woodside and Krischer’s models. Woodside model has a deviation of 7.8% and Krischer of 6.7%.
8.4. Models for mixtures:

8.4.1. Applied to Portland cement:

The models were applied to Portland cement in order to predict the value of thermal conductivity based on the mass fraction of cement, however, we do not have any experimental data to compare the models to. We suggest performing the experiment in order to pick which model is most representative. The most important thing to add is that Maxwell’s model seems to be a little stray from the other models; therefore, it might not be very representative.
8.4.2. *Applied to lime:*

Similarly, the models were applied to various mass fractions of lime to predict the thermal conductivity of the composite, however no experimental data were available to compare the models with. We suggest performing the experiment in order to pick which model is most representative. Again, Maxwell’s model seems to be a little stray from the other models, therefore, it might not be very representative, it all depends on the results of the experiment.

![Figure 28: Modeling effect of lime on thermal conductivity of clay](image)

8.4.3. *Applied to sheep wool:*

In this case, the series model was the most representative of the thermal conductivity of the composite clay-wool, however, the other models were far from representatives. This can be explained by the fact that in this case, heat flow is perpendicular to the wool.

![Figure 29: Theoretical and Experimental thermal conductivity of the composite clay-wool [16]](image)
9. Discussion:

All the models are representative of the compressive strength of our unfired clay bricks; the only one that may deviate is the water content model, as it starts diverging when water content exceeds 8%. However this will not be an issue since the percentage water content in our clay is between 4.5 and 6%, and it will decrease when we heat them at a temperature of 60 °C and sundried.

The results show that water content is most accurately predicted first using the weighted geometric mean model and then Krischer. This is an important finding and it has been attributed to the fact that water as a liquid mixes more homogeneously with clay.

Furthermore, it has been proven that the series model accurately predicts the changes in thermal conductivity of the mixture clay and wool. Wool as a fiber has a very low density paired with a remarkably low thermal conductivity; therefore it makes perfect sense that adding it to clay has yielded to the lowest value of thermal conductivity, given by the series model.

Concerning the additives cement and crushed limestone it seemed that Maxwell’s model deviated extremely from the other models therefore it was dismissed. This is due to the fact that cement and limestone powder usually take the shape of flakes and not spheres, Hamilton’s model can be a good indicator if we use a low parameter is sphericity between 0 and 1, if we assumed that the particles are dispersed randomly. Moreover, the series and parallel model are also good candidates to predict thermal conductivity of this composite material because their parameter is the direction of the heat flux. The juxtaposition of the series and parallel model may as well lead to interesting findings. [6] Willy and Southwick developed the first mixed model where heat flux is perpendicular, but traverses parallel layers disposed in parallel with other layers in series [6]:

\[ k_{eq} = \eta k_{\parallel} + (1 - \eta)k_{\perp} \]  
(34)

Such that \( \eta \) are the alternative parallel layers and \( (1 - \eta) \) are the alternative series layers.

Whereas Krischer proposes another model where heat flux is perpendicular traversing parallel layers disposed in series with other layers in series [6]:

\[ k_{eq} = \frac{1}{\frac{1}{k_{\parallel} + (1 - \eta)}k_{\perp}} \]  
(35)
Conclusion:

This project was a continuation of Dr. Khaldoun’s work towards providing energy efficient homes to the population of the village of Ben Smim.

This project aimed relies on using local, low embodied energy construction materials such as clay, which represents an essential step towards making houses more cost and energy efficient. The reason behind that is that clay is not only a cheaper alternative for cement, but it also offers many other advantages such as increasing the utilization of local material, reducing transportation costs as the production is in situ, good compressive strength, insulation and better thermal properties, less carbon emission and embodied energy in the production phase, an extremely low level of waste and finally no direct environmental pollution.

A study of this clay was conducted starting from identifying the type of Clay found in Ben Smim, to identifying its chemical composition, and its thermal properties such as thermal conductivity, heat capacity and density.

Afterwards, some mathematical models were developed to help predict some of the properties of the building materials, mostly compressive strength and thermal conductivity, based on the most important characterizations of clay namely porosity, water content and grain size. Recommendations were made to improve those properties that involved processing the material by ball milling or supplying it with natural additives namely sheep wool, lime and Portland cement (but only in small proportions).

Consequently, models were also developed to help predict the impact of these additives on the effective thermal conductivity of our construction material since, ultimately, our goal is to provide a housing with better thermal insulation that will reduce heating costs.

Finally, these models were compared to actual experimental data to see if they really predict those properties, some of the experiments could be performed while others were out of our reach so we used data available in our literature.
References:


Definitions:

*Bulk density:* Bulk density is defined as the mass of many particles of the material divided by the total volume they occupy. The total volume includes particle volume, inter-particle void volume, and internal pore volume. [9]

*Creep:* plastic deformation that happens slowly and under low stresses.

*Diffusion:* The phenomenon of material’s transport by atomic or particle transport from region of high to low concentration. [23]

*Lattice:* the regular geometric arrangement of points in a crystal space. [24]

*Matrix:* the continuous phase in a composite or two-phase alloy microstructure in which a second phase is dispersed. [24]

*Ball mill:* type of grinder used to crush materials into extremely fine powders.

*Phonon:* a phonon is a packet of elastic waves. It is characterized by its energy, wavelength, or frequency, which transfers energy through a material. This relies on the propagation of thermal vibrations through the crystal lattice across a temperature gradient, and is dramatically reduced when large numbers of point defects and extended defects (e.g., dislocations) are present.

*Mean free path:* The mean path is the average distance travelled by the phonon before scattering, the latter can be caused by defects, boundaries or other phonons.

*Pozzolanic reaction:* reaction between a pozzolan (Any of various powdered substances that react with lime to form strengthening or enhancing compounds in cement.) and \( \text{Ca}^{2+} \) or \( \text{Ca(OH)}_2 \) in the presence of water.

*Embodied energy:* The sum of all energies required to produce goods.

*Hygroscopic:* Hygroscopic is the quality of the material to absorb water from its surrounding.

*Atterberg limits:* Atterberg limits test aims to compute the plastic and liquid limits. These limits are based on the moisture content of the soil. The plastic limit (PL) is defined as the moisture content where the soil changes from a semi-solid state to a plastic state while the liquid limit (LL) is defined as the moisture content where the soil changes from a plastic state to a viscous fluid state.