CLAY-VER

To build with what is under our feet

An exploration of the use of excavated clay for the indoor climate in Göteborg and its application

MATHILDE GRUNACKER

Chalmers School of Architecture I Department of Architecture and Civil Engineering

Examiner : Krystyna Pietrzyk
Supervisor : Walter Unterrainer I Co-supervisor : Shea Hagy

> “
>
> *All things come from earth and all things go back to it.*
>
> Ménandre, 342 B.C -
> Greek Dramatist
>
> ”

CLAY-VER, From ground to building
An exploration of the use of excavated clay for the indoor climate in Göteborg and its application
MATHILDE GRUNACKER

Chalmers School of Architecture
Department of Architecture and Civil Engineering
MPDSD, Master’s programme Architecture and Planning Beyond Sustainability
Direction : Building design for sustainability

Examiner : Krystyna Pietrzyk
Supervisor : Walter Unterrainer
Co-supervisor : Shea Hagy

ABSTRACT

Humanity is facing one of the most crucial challenges ever known: tackle global warming. Emissions from the construction field increase every year and represent 39% of the overall CO_2 emissions in Europe.

To reduce its impact, a building must not only achieve low operating energy but also take into account the material's low embedded energy, a high circularity potential, and a healthy indoor climate. Aware of this, the city of Göteborg has initiated a project to build a fossil-free preschool: the Hoppet Project. Here, such as in many cities, a large amount of clay is excavated each year for different buildings and infrastructure projects. While clay is a natural material and a resource, it is considered as waste and must be cleared out of the building site. An initiated project, "Recirculate", aims to find new use for that clay, and works in collaboration with the Hoppet project.

Within this frame, the objective of this master thesis is to highlight the potential of excavated clay for the benefits of the indoor climate. Indeed, clay has always been used and has very good properties which participate in low-tech climate regulation. It wants to encourage the use of clay waste to build sustainable buildings suitable for temperate and cold climates like Göteborg and to make more reasonable use of resources.

Literature research, field tests, and case studies frame the potential use of clay waste and its properties, with an emphasis on indoor climate. Based on this exploration, a catalog of clay material solutions is compiled to show where and how it can be used and to illustrate its aesthetic potential. This document is then used to develop a generic design proposal, which is a testbed on the Hoppet project. This testbed aims to explore possible clay implementations in an adapted way for the indoor climate and to propose an answer to the question. Finally, comparisons with the original hoppet materials show that clay is relevant in a fossil-free and zero-emission concept.

Those elements are expected to be used references to promote these materials, increase awareness, and inspire to build for sustainability.

Key Words: Excavated Clay - Natural Material - Circular material - Health - Indoor Climate - Testbed - Preschool

ACKNOWLEDGEMENT

Writing this master thesis was a real challenge but also an interesting and enriching process. I would like to thank those who contributed to this work :

First of all, my supervisor Walter Unterrainer, for the interesting discussions during the tutorials, for his significant support and guidance. Thanks for his involvement and his availability during this semester.

My co-supervisor, Shea Hagy, for his enthusiasm and positive energy shared on my work, thanks for sharing with me his expertise about clay construction.

My Examiner Krystyna Pietrzyk for her advice during the presentations and interesting feedback.

I would also like to thank all the people with whom I exchanged about the subject by e-mail or during interviews.

I'm also grateful to my friends and Florian, for their support and interesting discussion during this process, but also for the good times during my years of study, whether in Geneva or here in Göteborg. They were a great source of inspiration.

Last but not least, I would like to thank my parents, Régine et Henri, for their unwavering support since always and particularly during these years of bachelor and master. I thank them for always believing in me and for teaching me to do the same.

STUDENT BACKGROUND

PERSONAL BACKGROUND

I was born and grew up in the French Alpes countryside. When I was a child, I used to spend a lot of time outdoor, enjoying nature and its benefits. I was afraid to see my favorite natural element, snow, threatened by global warming. I already wanted to make it change. This is without any doubt one of the reasons why I'm here now, studying sustainable architecture. I strongly believe that architects have an important role to play in reducing the impact of this field, and if something remains possible, I want to be part of it.

ARCHITECTURAL WILL AND INTEREST

I am in search of a sustainable architecture that could lead to a more rational and reasonable way of building. I discovered natural building materials during my Bachelor's degree. Now I'm fascinated by the amazing possibilities and solutions it creates for our field. During my days at Chalmers, I've tried to work with them as much as possible across various projects, and my interest grew up even more toward earthen materials.

EDUCATION BACKGROUND

Interships

2014-2015	Matei AGARICI Architectes Geneva, Switzerland
2018-2019	BUNQ Architectes Nyon, Switzerland (half time with my study)

Education

2015-2019	HEPIA (HES-SO) Geneva, Switzerland Bachelor of Arts in Architecture
2019-2021	Chalmers University of Technology Gothenburg, Sweden Master of Science in Architecture and Planning beyond sutainaibility

BACKGROUND AT CHALMERS

Studios

Fall 2019	Planning and design for sustainable development in a local context *Local context - Meeting place - Circular economy - Natural material*
Spring 2020	Sustainable architectural design *Pre-school - Education - Scale - Zero Energy Building - CO_2 storage - Indoor climate*
Fall 2020	Future vision for healthcare : housing for Elderly *Monastery - Courtyard -Living quality VS Medical institution - Momy feeling - Natural material*
Spring 2021	Master Thesis Building design for sustainability

FIRST APPROACH

Image 1. *Rammed earth sample realized by the EarthLAB and the Author, using clay from Göteborg (Picture : Author, 2020)*

Before the start of the master thesis semester, I was invited to participate in the ramming of a small earth sample developed by EarthLAB, using clay from Göteborg. It was my first experience with earth used as a building material and my first contact with the local clay. It was interesting to see and understand how the clay has to be completed and corrected with a precise proportion of sand, gravel and water. I was also able to experience the energy necessary to rammed the earth. This sample testified of the beautiful color and result the ramming, without the addition of pigments.

CONTENT

1

Introduction

This chapter is an introduction to my work. It aims to give the background of this master thesis both from a global and a local scale. The thesis question is exposed as well as a description of the method, goals and scope.

GLOBAL CONTEXT

The XXI century is the most crucial time ever for change.
Humanity needs to initiate actions to change the way we live to preserve our planet, our environment, our future, and the next generations. World population is growing exponentially, and planetary boundaries are overshot each year earlier. To reduce earth's pressure and to limit global warming under 2°C since the industrial revolution, we need to make a better use of the resources and decrease CO_2 emissions.

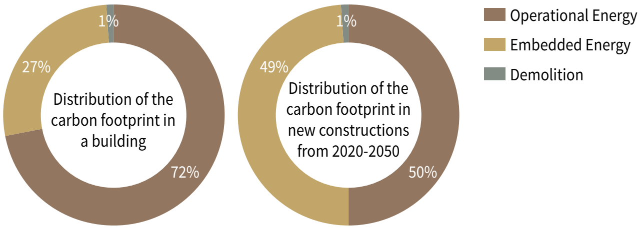


Figure 1. *Evolution of the distribution of the carbon footprint in buildings (Data from Architecture 2030 & UN environmental status report 2017)*

NEED FOR A SHIFT

According to the UN Environment, 230 million sqm of buildings are expected to be built by 2060 (UN Environment et al., 2017) and the building sector is responsible for 39% of the CO_2 emissions (Global ABC et al., 2019). Therefore, we need an urgent shift in the ways we build to decrease the emissions whilst still sustaining our need.

CONVENTIONAL BUILDING

Conventional buildings are made of non-natural materials (such as concrete, steel, glass, or plastic) often fossil-based. They need a lot of transformations and imply important CO_2-eq emissions* in their life-cycle. Such buildings can be energy efficient during their usage stage but on the other hand can have an important amount of embedded energy* (material resources).
Indeed, in the past, the operating energy* (usage stage) represented the largest part of a building's emissions. Therefore, standards have focused on improving the energy efficiency without considering the embedded one. Consequently, the part of the operating energy in the building life-cycle* emissions is decreasing and the embedded will soon represent the half of it, *Figure 1*. Thus, to decrease the impact of buildings in the future, it is now important to consider also the amount of embedded energy.

SUSTAINABLE RESOURCE MANAGEMENT

Material choice is therefore really important in sustainable building design. Going for more natural, renewable, and local resources for material would decrease the impact and lessening transformation and transport. On top of that, because they need fewer transformations, natural materials are most of the time circular* and can be reused after usage with no or little injected energy.

HEALTH

People in our society spends more than 90% of its time indoors. Accordingly, the indoor environment needs to be as healthy as possible and suitable for the activities hold in it. As stated by the WHO (World Health Organisation) bad indoor conditions can lead to respiratory symptoms, nervous troubles, or even cancer and cardiovascular diseases. A good indoor climate* is especially important for kids, the elderly, or other vulnerable people (World Health Organization, n.d.). Indoor climate is defined by several environments: thermal, atmospheric, acoustic, actinic and mechanical, and is describe more in depth on p.22-23. Energy efficiency standards, introduced before, often lead to a lower air quality by the presence of chemicals and non-breathable envelopes. Conventional buildings make use of a lot of equipment and artificial strategies to keep a comfortable indoor climate and often release harmful substances while natural materials do not. They have really good properties that can easily increase indoor climate quality and in certain cases decrease energy consumption too.

CLAY BUILDING

For those reasons, clay presents an interesting sustainable potential. Earthen materials, which were previously left behind for the benefit of modern materials, are tending to come back in

> “It is of crucial importance to bring the built environment into a low carbon roadmap. This will be achieved first of all through highly energy efficient buildings. It is also through a complete rethinking of the design of the buildings, based on low carbon solutions
>
> - Pierre-Andre de Chalendar -
> Chairman and CEO of Saint-Gobain”

modern architecture. What is the role of clay in earthen architecture ? Clay is the binder of the earth. In other words, it is to earth what cement is to concrete. Cement alone represents 5% of the man-made greenhouse gases and it is stated that cement concrete is the second most important necessity for humans after water. (Boltshauser, R., Kapfinger O., et al. 2011) Clay, on the opposite, is natural. It is estimated that 50% of the world's population lives in earthen buildings. It has been used since the first civilizations settled down in Mesopotamia, 9000 years BC and remains of earthen buildings are found on all the continents. Earth is a natural material available everywhere and therefore very local. Its implementation in buildings requires low transformation (when used raw). It is the ultimate circular material because it does not lose any property as long as it is not baked or stabilized. Thus, it can be reused endlessly or returned to nature after use. On top of that, it presents really good properties for the indoor climate and health benefits.

THE ACTUAL SITUATION IN THE FIELD

Earthen architecture sees a resurgence of interest since the beginning of the century. Stakeholders in the field see in it a great potential for sustainable building models and few examples of modern earthen architecture are built in Europe. It presents so many interesting properties that need to be further investigated. There is a lot of research potential on the best possible use of it such as indoor climate properties, creation of new materials, possibilities to make it stronger without cement stabilization, to name a few. It is almost an endless topic and research is important to promote it and make it accessible. Indeed, earth still faces many obstacles for a wider use. The main problem is the difficulty to make generalities, each earth around the world has specific properties, making difficult the setting of standards. Beside, it has a negative image in some regions of the world : it is considered as the building material for poor people.
Fortunately, thanks to a lot of research groups such as CRATerre in France, the creation of awards, such as the Terra & Terra-Fibra Awards, or the craft man experience of the famous clay builder Martin Rauch, the knowledge expansion is possible and step by step “up-scaling” earth is possible. This field still needs a lot of research and innovation to make it move forward.
The resource management field also has seen a new discussion in recent years, that increases and supports the relevance of earth as a building material. The needs for new buildings and infrastructures in cities around the world leads to the excavation of an inconsiderable amount of earth each day. Legally, this earth is considered as waste and the normal way of proceeding is to dig, to dispose excavated material and to build. The disposal steps often require earth to be moved far away from the building site, generating CO_2 emissions for transport. This earth is a resource which with better management can be used in building constructions. Few projects are working on this idea such as “Cycle Terre” in Paris or “ReCirculate” here in Göteborg. In this thesis, field tests with excavated clay from the city will be done to see if it can be suitable to build with and relates to that discussion.

Material	Embedded carbon in production (kgCO_2/t)
Cement CEM I	838
Lime	689 - 776
Gypsum	140
Sand	11
Raw earth	5 - 11

Figure 2. *Embedded carbon in different materials (Adapted from Pradenic, 2020)*

LOCAL CONTEXT

> “
>
> *The City of Gothenburg is to build a preschool which, as far as possible, is fossil-free at all stages*
> *-Any climate impact should be compensated.*
>
> - Political decision of Göteborg City -
> Cited in Arentsen A. K. , 2019
>
> ”

CITY GOALS

Within the sustainable development frame and neutral-climate goals, the city of Göteborg plans to reduce its greenhouse gas emissions to a rational and sustainable level by 2050. In 2014 it was evaluated that every year the city of Göteborg releases around 2.5 million tons of carbon dioxide equivalents of greenhouse gases, which is expected to be reduced by 75% by 2050. (City of Göteborg, 2015)

HOPPET

In that context, Hoppet is a full-scale research project aiming at the construction of a fossil-free preschool. It lays on the experimentation of materials to research, develop and promote the knowledge and the possibility of building with fossil-free resources. The result and the new findings of this project intend to be used in several future projects of the city, with a long term perspective to make 100% fossil-free building a norm.

The actual preschool project is located in Hisingen and is under development. The project targets to be as fossil-free as possible for all the stages:

- Product manufacturing
- Product transport
- Building process.

In the process, the materials normally used in a preschool were studied. According to Nina Jacobsson Staålheim, it was pointed out that 150 out of 200 materials need to be replaced to achieve fossil-free targets (Nyborgg, n.d.). The project investigates how to replace and optimize those materials to reach the objectives. Even if “fossil-free” does not mean “zero emissions”, the project also aims to minimize CO_2 emissions.

CLAY EXTRACTION

Västlanken is a major mobility infrastructure project in Göteborg. It consists of the creation of an underground railway in central Göteborg. The aim is to increase the capacity of everyday travelers and reduce the commute time and cars in the city center (Trafikverket, n.d.). That project alone foresees the excavation of around 1 500 000 m^3 of underground materials (Matsdotter, V., 2020). The amount of bricks that could be made from this is forty times the amount of bricks used for Stockholm City Hall, *Figure 3*.

Besides, the city of Göteborg forecasts 150 000 new residents by 2035. Therefore, the city planning development foresees between 70 000 and 80 000 new homes in the area by the end of that period (Kant H., 2020). Each of these new buildings will require a site excavation for the foundations that will dig up even more earth.

In Göteborg, due to the geological context, the excavated material is mainly composed of clay. This extracted clay is useless on the building site and is considered as waste that needs to be evacuated as soon as possible. Storage places for this kind of materials are often remote and therefore a large number of round trips by truck are required to evacuate all the materials.

Following the circular economy concept, that clay represents a resource. Reusing it within the city could help to decrease the CO_2 emissions of such a project, but also those of future buildings that could use these materials. In Göteborg, the Recirculate project is currently studying how these excavated materials could be reused in the local area of the city. The Hoppet project is also working in synergy with the Recirculate project to see if clay could be implemented in the school. This master thesis is included in that context.

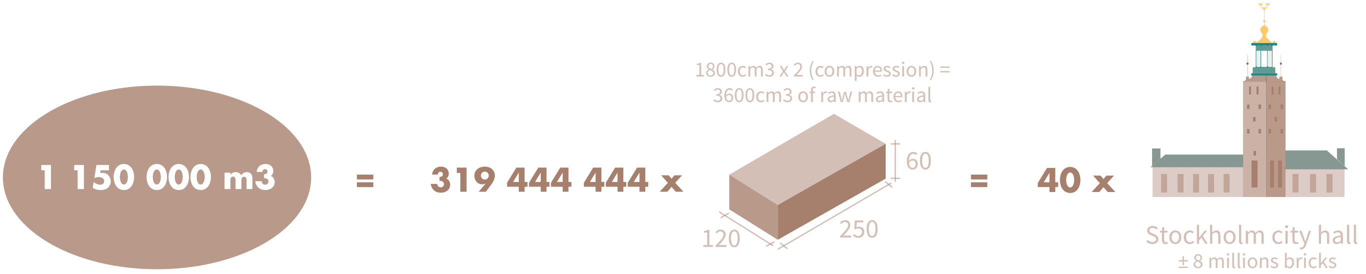


Figure 3. *Amount of extracted earth in the Västlanken project (By the author, data related to the city hall from Sampson, A. 2015)*

RELEVANCE FOR THE MASTER THESIS

The indoor environment, that is described in page 23 22-23 is very important for kids, both for their health and their capacity to be efficient and to learn better.

Furthermore, in schools, there are many interesting variations in terms of indoor climate such as hours and occupancy levels that change constantly throughout the day. Clay is known for its good properties on indoor climate regulation, and Göteborg city planning development forecasts the evacuation of a huge amount of it. This is why research work on how to use excavated clay for the benefits of the indoor climate seems to be a relevant proposition to reduce the impact of building constructions.

To do so, this master thesis uses the Hoppet project as a tool : a demonstration project or a testbed to present and experiment in design the possibility of using clay extracted from the city for the benefit of the indoor climate.

Image 2. *Hoppet preschool in Hisingen (Render and project : Link Arkitektur)*

THESIS QUESTION

How to promote the use of excavated clay for buildings and take advantage of it to optimize indoor climate in sustainable buildings in a Swedish context ?

MASTER THESIS GOALS

Assess, optimize and promote clay properties on indoor climate in the context of Göteborg.

Define strategies with clay adapted to the Hoppet project's indoor climate

Compare the strategies with what was already designed in terms of embedded energy

Demonstrate the beauty and variety of clay to increase awareness especially among the skeptical.

Valuate a material that is too often considered as a waste

Figure 4. *Thesis goals (By the author)*

METHOD & DELIMITATIONS

INTRODUCTION

Here is a description of the methodology used to carry out this master thesis. Different approaches were first applied to increase my personal knowledge and understanding of the materials in order to be able, in a second time, to translate them into a demonstration project.

THEORY

Literature studies have helped to define and to frame the context and the potential of earthen materials in construction. They also made it possible to understand the material as well as its characteristics with regards to the indoor climate and the circular economy.

SAMPLING AND TESTING

In this step, limited scale tests increased my knowledge about local clay, in order to understand how it is composed and whether it can be used for building.

CASE STUDIES

Case studies complete the theoretical research. The study of constructed examples is used to outline and analyze how clay can be used in a common way as well as describe the effective benefits on indoor climate.

CATALOG

The Catalog consists of a range of clay building elements which are used in construction for various purposes. This part aims to illustrate the possibilities and also to promote techniques currently less known.

GENERIC DESIGN

This part aims to bring together the knowledge of the previous parts in design to see how clay can be implemented to benefit the indoor climate. A proposition is applied to the Hoppet project which is used as a testbed. A quick need analysis of the pre-school was made in order to propose a relevant use of clay in relation to a specific need.

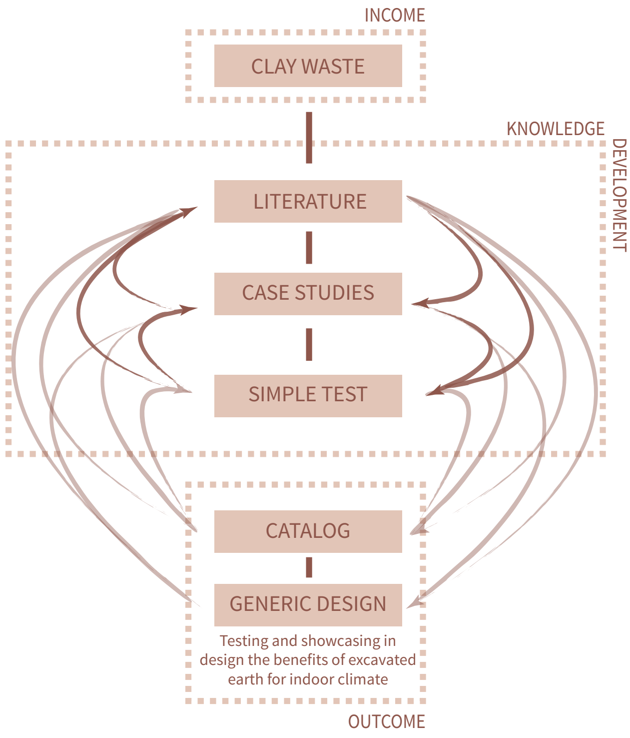


Figure 5. *Process of the thesis (By the author)*

Figure 6. *Thesis delimitations (By the author)*

2

Clay in theory

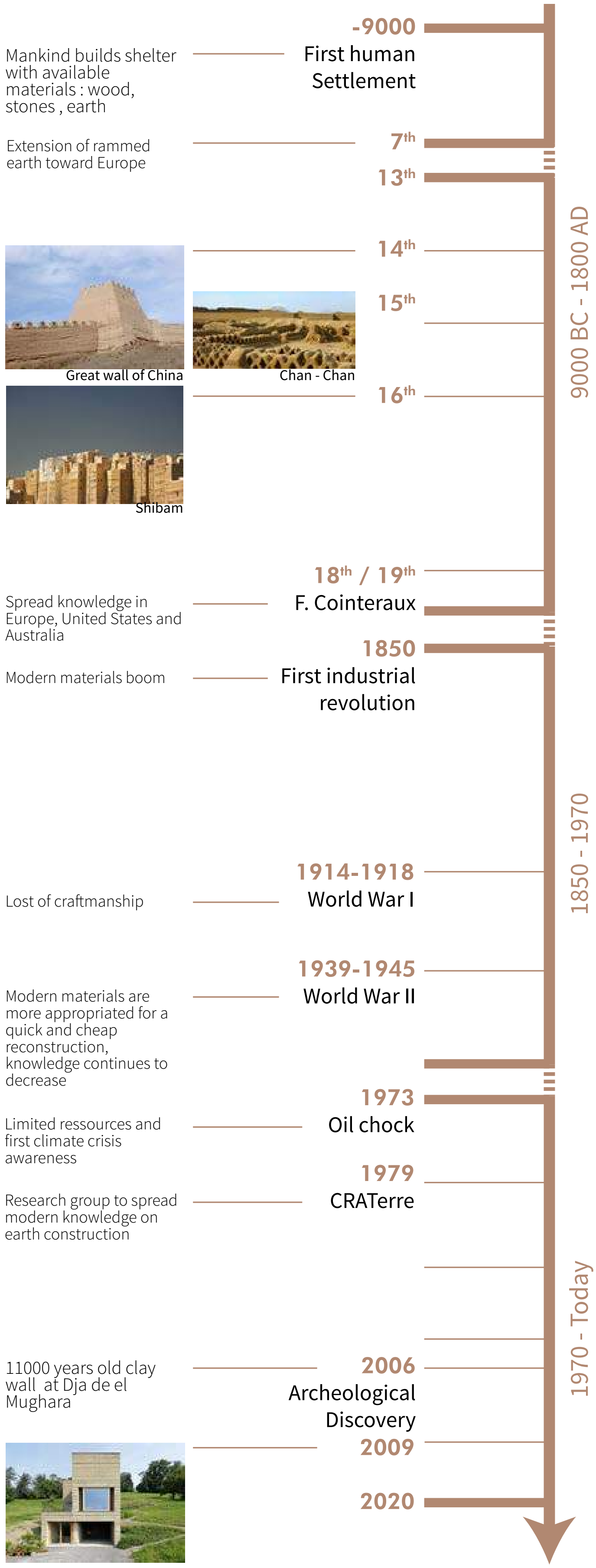
The aim of this chapter is to give a comprehensive overview of clay as a material in building construction. Based on literature studies, clay is described in its different scales and uses. The description of its properties is an important part of the chapter and is highlighted from an indoor climate perspective. The local geology and clay formation in the region are also approached to relate to the context and enhance the relevance of this research in the local area of Göteborg.

CLAY IN THE WORLD AND HISTORY

Figure 7. *Earth construction worldwide (Adapted from Fontaine, L. et Anger, R. ,2009)*

Earth in building has been used for a very long time. It was probably one of the first material used for building when the human settled down. Different techniques have been developed depending on the area and the quality of each earth. The use of earth in construction has known various successes throughout the ages. It has been forgotten during the 19th and 20th centuries in favor of modern materials such as steel and concrete, which better responded to the modern revolution and the need for post-wars reconstruction. At that time, however, in scarce regions it was used abundantly because of it was the only available material. Since the late XXth, renewed interest is visible due to the urgency of the climate crisis, and architects now tend to use earth in a modern way. This material is present all over the world and, therefore, is a local material almost everywhere. The map above highlights a presence mainly in the southern hemisphere, where temperatures are warm and the climate is drier. But it also shows that it is used in colder and more humid climates like in Europe. We can even notice their presence in northern Europe and here in southern Sweden. It shows that it can also be relevant to use it in such a cold and humid climate and that it is also part of the culture.

It is estimated that 50% of the world's population lives today in earthen buildings. In addition, 15% of the buildings on the UNESCO heritage list are made of earth (Fontaine & Anger, 2009). This testifies of the high architectural quality of the material as well as its resilience.



BIRTH AND DEVELOPMENT

The first humans settled down in the Mesopotamia area. Wood was very scarce in this arid climate and shelter was therefore made with an available local material : earth. It was implemented differently depending on culture and civilization : Cob, Adobe, Rammed Earth and other techniques have then been spread across the world. For instance, Rammed Earth that was used in northern Africa from -100 BC, and was spread in Europe around the 7th century. Nowadays, a lot of ancient earthen buildings remain, testifying of a big life span resistance. An example of this is a section of the Great Wall of China, built in desert area, made out of a type of rammed earth. In Shibam, buildings of 30m high were built. At this time, hygro-thermal properties of earth were already known and discussed. Earth was already described as being good for thermal comfort.

DECLINE

Earth has always been suitable to human needs in each time but in the 19th and 20th century, several events have lead to the cultural amnesia around the material. The first one is the Industrial Revolution and the new materials that were developped and promoted. Using them was a synonym of wealth and modernity and oldest tradition has decline. Then during First World War, a lot of men died and craftsmanship knowledge with them. Finally the real knockout was after the Second World War. Europe was facing an emergency of reconstruction, prioritizing materials that are quick to implement such as concrete. However, in some parts of Germany, cheap and homemade techniques were used in these difficult times due to the poverty engendered by the war. Linking materials to poverty.

REVIVAL

The first oil shock, rising awareness of climate change and the need for sustainability opened up new perspectives on the use of earth in construction in developed countries. Indeed, the low amount of embedded energy and the potential to limit operational energy are interesting properties to be part of a solution to face the climate crisis in the building sector. Several research groups have been formed and are trying to promote and simplify the construction procedure of a material that still need to win the trust in countries where the building sector is subject to a lot of standards. While it is a cheap material in some parts of the world, it is a material that is very labor-intensive and therefore very expensive in high-wage countries. Innovation to upscaled the material for tackling down this problem is essential to increase its credibility.

Figure 8. *Time line of earth construction (By the author , Data from Fontaine, L. et Anger, R. ,(2009) - Minke, G. (2009) and all)*

WHAT IS CLAY ?

On the planet there are many different varieties of earth : each one is made of a different mixture of various grains and minerals of different sizes, in various proportions. Therefore, specific names are used to characterize them : "clay" is one of them, and "earth" is the generic word to group them all, Figure 9. The main common earthen components are sand, gravel, silts and clay. Sand, gravel and silts form the skeleton, while clay is the binder that links them together. (Fontaine & Anger, 2009).

DEFINITION

When an earth type contains a significant amount of clay particles, it is common to use the word "clay" to refer to that soil. But that does not mean that it contains only clay particles. *Figure 9* shows the different names given to an earth based on its specific composition. According to SGI (Swedish Geotechnical Institute) most of the earths that are found in Göteborg are clay.

CLAY PARTICLES

Clays particles are the smallest kind of grain in the natural earth composition, they are invisible to the naked eye. Clay minerals are smaller than 2 µm. There is a wide variety of clays and their type, color, shape, structure, and size may differ depending on the climatic context, altitude, minerals, and geological factors (J. Eid, 2019).

STRUCTURE

Clay particles have a very specific structure which makes them completely different from other components of earth. There is a wide variety of clays but they all have their small size and similar structure in common. They are made of primary lamellas (or plates) which are aggregated into an elementary structure. Particles are the result of the aggregation of several elementary structures together (Röhlen, U. et all, 2013). Due to this specific arrangement, clays belong to the "phyllosilicates" mineral families. (Van Damme, 2013).
The primary plates can be of two kinds, see *Figure 10* :

- Thetrahedrique lamella (T) : formed of several Silicates (Si) surrounded by oxygen anions (O2-)
- Octaedrique lamella (O) : formed of several aluminum (Al) surrounded by hydroxyls (HO-)

Those two types of structures bind together in the form of T-O (two-layer particles) or T-O-T (tree layer particles) to create the elementary structure. Two elementary structures are separated by an inter-layer space as shown in *Figure 11*. The strength of the loam depends on the kind of ions bond between the lamellas as well as between the elementary structure, and therefore depends on the type of clay (Minke G. 2009). Generally, three-layer particles present a higher ionic binding capacity.
According to the SGI, the most common clay minerals are (Swedish Geotechnical Institute SGI, 2004) :

- Kaolinite (non swelling, 2 layers)
- Illite (non swelling, 3 layers)
- Smectite (swelling, 3 layers)

ILLITE

The most common type of clay in Sweden is Illite (SGI, 2004), due to the Ice Age and is often used in earthen constructions (D. Muheise-Arralia, 2020) Illites are made of a T-O-T structure that contains potassium k+ cations in the inter-space (SGI, 2004). Elementary structures are linked together by the Van der Waals forces, making them stronger. It is a non-swelling kind of clay : the k+ cations have the same size as the interspace, leaving very small space for water to come in between and make the clay swell. (Eid, J. 2019) Also, three-layer particles have a high specific surface, which increases the ability to absorb moisture from the environment (Röhlen, U. et all, 2013).

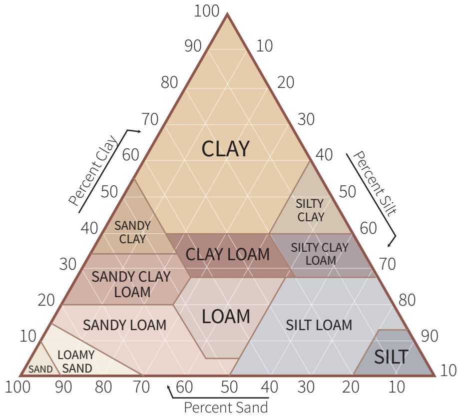


Figure 9. *Earth characterization (Adapted from Minke , G., (2009))*

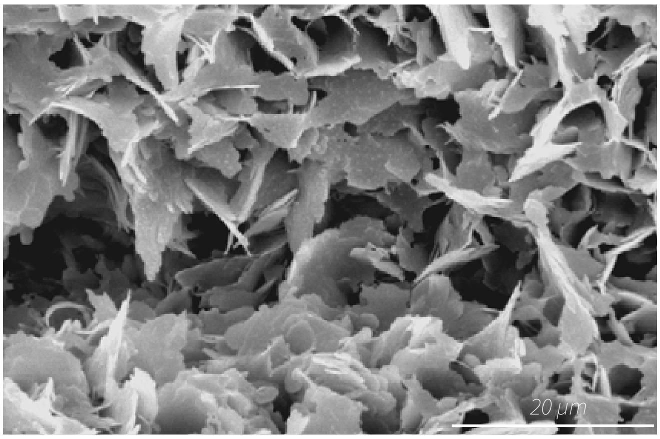


Image 3. *Illite under a microscope (M. Roe, Mineralogical Society n.d)*

CLAY AND WATER

The structure of clay and the ionic bond properties allow it to be activated in presence of water and to change of state.
When clay is in contact with free water, the different particles move away from each other and it becomes more or less liquid depending on the amount of water. When it dries, the particles realign themselves into a parallel shape as they get closer and electrical bonds are created. Clay can be in various states:

- Viscous when it is mixed with an important amount of water,
- Plastic with less water,
- Humid with low amount of water
- Formed and dry (or baked) it becomes solid and can support weights.

That last part is interesting for a sustainable approach: unlike cement, clay does not necessarily need to be fired to activate the bond which saves a lot of energy.

There are different kinds of water in earth (Minke,G., 2009) :

- Water of crystallization : which is structural. This is what creates the chemical bond between the plates and also defines the states of clay which are described before. Clay needs to be heated above 400°C to remove that water. In that case, it breaks the reversibility properties.
- Absorbed water : electrically bond to clay mineral. This one is fully released when heated up to 105°C and it will not change the state of the material even under 90% of humidity. That means that even in a very humid area, the material will not swell.
- Water of capillarity : water which penetrates the pores by capillary action and which is fully released when heated up to 105°C.

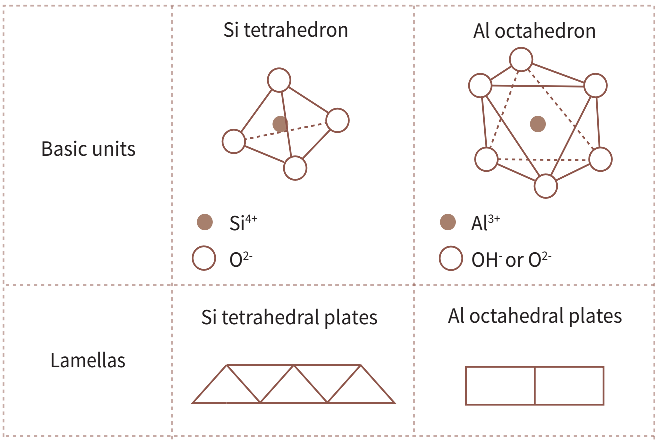


Figure 10. *Basic units and primary lamellas formation of Illite clay (Data from Minke , G., 2009)*

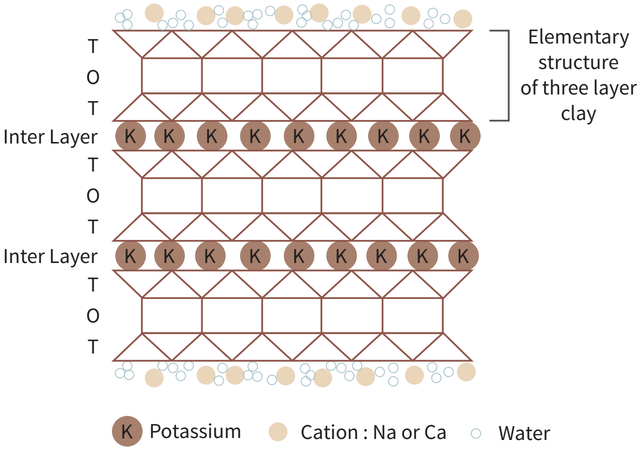


Figure 11. *Particle of Illite clay made of several elementary structures (Adapted from L. W. Diamond, 2008)*

CLAY FROM GÖTEBORG

CLAY STUDY

Many studies are being carried out on Göteborg clays because there is an important amount of infrastructure projects that require to dig into it. The Göta tunnel was built a few years ago and needed extensive clay excavation and studies. Now the Västlanken train project is under construction and is expecting to dig out 1 500 000 m^3 of clay. (Matsdotter, V, 2020) However, these studies mainly concern the possibility of building into the clay or on the clay, but not of building with clay.

GEOLOGY

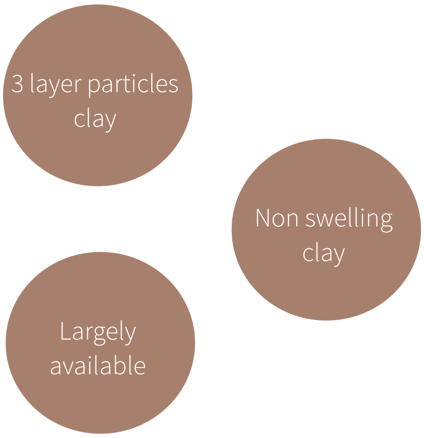
As shown on the map below, *Figure 12*, Göteborg's soil is widely composed by clay. This is due to its geographical and geological context. Like a lot of northern areas, it was covered with ice during the last age of ice. And this is one of the conditions for the formation of clay. On top of that, the city's coastal location gave the clay another characteristic: Göteborg's clay is known to be a "Quick Clay", and is described in the next part (Karstunen M., 2019). As said before, clay soils are only composed by clay, and the Göteborg clay is also composed of silt and a bit of sand.

QUICK CLAY

We now know that most Swedish soils are Illite and that it is a non-swelling clay. Non-swelling clays are a predominant condition for the formation of Quick Clay (SGI, 2004). It is a kind of clay that is formed in a salty environment. At the end of the Ice Age, melting ice carried a lot of sediment which then settled at the bottom of water streams and in the sea. At the time, the Na+ content of the water in the clay was high which increased ionic forces by neutralizing the negative repulsion (SGI, 2004. With the end of the glaciation, the sea level fell, changing the context for the soil. In this new context, clear water from rivers and rainfalls was able to penetrate the soil, washing the Na+ out from the clay and thus reducing its ionic forces as well as its shear strength (SGI, 2004).

The main characteristic is that it can have a sudden change of consistency and can change from a solid state to a liquid state by a modification of mechanical stresses. This is why quick clays are often the cause of sudden landslides.

This property could be a problem when it comes using this clay in building materials and would require further investigations. However, experiments show that after applying a load to a quick clay cylinder, making it collapse and remold, adding salt to the mixture would make it hard again (NGI Norwergian Geotechnical Institute, n.d). Thus, it seems to be possible to correct this property easily. It may be interesting to study this effect more in the context of another research.



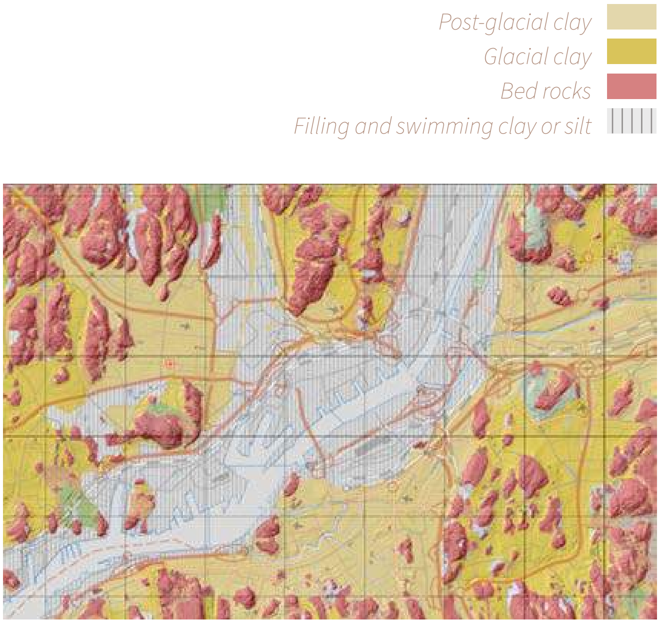


Figure 12. *Geological map of Göteborg (By SGU)*

CLAY IN BUILDING

ROLE IN CONSTRUCTION

The ionic connection that occurs between the particles gives the clay binding properties and is the reason why it can be used for construction.

In earth constructions, clay is what is called the colloidal agent (same role as cement in concrete) and needs water to be activated and thus to create strong bonds with other components of the loam. In other words, clay is to earth what cement is to concrete (Fontaine & Anger, 2009). That property allows the use of clay in construction in different shapes and methods, depending on its state (humid, plastic, viscous) or its composition.

Clay can be used in various building elements and different techniques are discussed in the chapter “Catalog” :

- Structural work : Load bearing walls, slab
- Interior work : partition wall, acoustic panels, floor screed...
- Finish : plaster, flooring, ceiling

SUITABILITY FOR BUILDING

Each type of clay has different properties. For example in the single city of Göteborg, depending on the site where the earth is taken, the suitability for building material is not the same. Laboratory ZRS performed simple tests on two clay samples : C1 was collected near central station, and C2 at Olskroken (see Appendix A). The locations of the two sites is quite close, yet C1 is considered unsuitable for construction due to a high ratio of organic component, while C2 is fine to be used (ZRS, personal communication). It highlights the importance of testing the earth in every situation. In a first stage, simple field tests can be done to see whether the earth seems suitable to use. Such tests are presented in Chapter 3 with earth from a third site in Göteborg. Then more extensive testing is needed to confirm suitability. This point is one of the main obstacles to the up-scaling and spread of modern use of earth : testing involves time, money and manpower (Rodrigo Fernandez, Terrabloc, 2020, Personal communication).

The main characteristics for an earth to be used in buildings are :

- No presence of organic components
- The cohesive properties of the clay (respectively described as a fat, almost fat or lean clay for high, medium or low cohesion)
- The amount of clay particles compared to other components
- The amount of salt is often subject to many discussions. Indeed, some think that it is necessary, others say that it is useless or even that it needs to be absolutely avoided, finally some say that it doesn’t matter. However some earthen building materials have a salt content limit to respect.

We saw that Illite is the most dominant kind of clay in the area, in *Figure 13* are summarized the characteristics of Illite clays according to what has been found in literature and developed in the sub chapter “What is clay”. It describes the pros and cons of each property for building. According to this table, Illite clay seems to have fairly good quality for building, the most important one being the cohesive properties.

Characteristic	Illite	Pros	Cons
Layer	three layer	Better capacity to bind componants of the loam	Could have a too strong cohesion, depending on earth’s composition
Type	Non swelling	Reduce the shrinkage effect of the clay when drying	Lower humidity absorptions compared to swelling clay
Specific surface	100m2/g	Important surface to capture and store humidity	
Bond link	K+	Van der Waals links, increases the rigidity of the materials	

Figure 13. *Illite properties (By the author, Data compiled from Eid, J. (2019) Minke,G., (2009), SGI (2004), Röhlen, U. et all, (2013))*

Image 4. *C1 , Clay from central station (Picture from ZRS, Personal communication, 2020)*

INDOOR CLIMATE

> “
>
> *The indoor climate is important for health, well-being and productive work.*
>
> - World Health Organisation (WHO) -
>
> ”

INDOOR LIFE STYLE

Nowadays, people are spending more and more time indoor, and this is especially true in cold climates like Sweden where people are estimated to spend more than 90% of their time indoor (Minke, G., 2009). This is even more true since the corona virus pandemic. Furthermore, architecture has always aimed to shelter human activities, and thus offer to people a place to be safe and protected from the outside environment. *Figure 14* shows that indoor climate is an architectural concern and a purpose in the same way as the Vitruvian principle of architecture. However, it is estimated that indoor air quality and climate today are often five to ten times worse than outdoors one (K. Steemers, 2021). Therefore, occupants' comfort should be a design priority. In a sustainable approach, providing comfortable, healthy and low energy indoor environments is important both for the health of the population and for ecological reasons.

It is known that earthen material ensures a healthy indoor climate and, to some extent, can participate in the reduction of the energy consumption thanks to specific properties. Strategies that exploit those properties have been used in vernacular architecture for a very long time. Using earth as a material can be challenging in a wet and cold area such as Göteborg but earthen buildings have already been constructed in humid and cold climate and testify that this is possible.

WHAT IS INDOOR CLIMATE ?

Indoor climate is a wide topic and involves many aspects. It has an impact on health, comfort and happiness of occupants. It also affects the productivity and efficiency to perform a task in a given environment (Nilsson P.-E., 2003). WHO (World Health Organisation) says that the indoor climate is particularly important for children, elderly and all vulnerable people. A poor indoor climate can cause minor disturbances (headaches, irritation of skin or mucous membranes, abnormal fatigue) or major ones by increasing the risk of cancer or cardiovascular diseases (Nilsson P.-E., 2003). In Germany for instance, two million people suffer from illnesses related to the bad indoor climatic conditions (Röhlen U., Ziegert C., 2013)

According to the WHO indoor climate is made up of different elements of the physical, chemical and biological environment which are presented in *Figure 15.*

For some of these elements, one can instantly sense if something is wrong : for instance if it's too cold or too dark. However other aspects are less known and less obvious to users but are just as important in terms of impact on health, such as the humidity level in a room. Generally, the various parameters of the indoor climate are regulated with ventilation, heating and cooling systems. There is a debate on the use of low-tech systems versus high-tech for the regulation of these parameters. However, vernacular techniques, such as the use of thermal mass or hygro-thermal properties of earth can promote a good indoor climate in a low-tech approach or complement a high-tech system. On *Figure 15* the parameters that can be improved by earth are highlighted in blue.

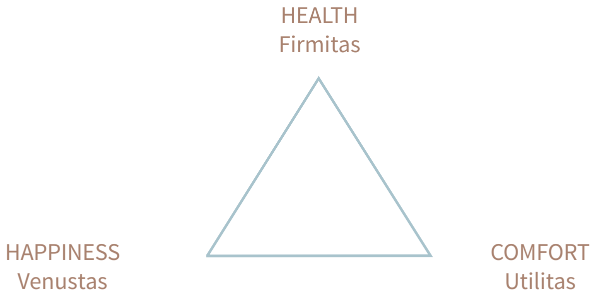


Figure 14. *Vitruvian principle of architecture and indoor climate (adapted from K.Steemers, 2021)*

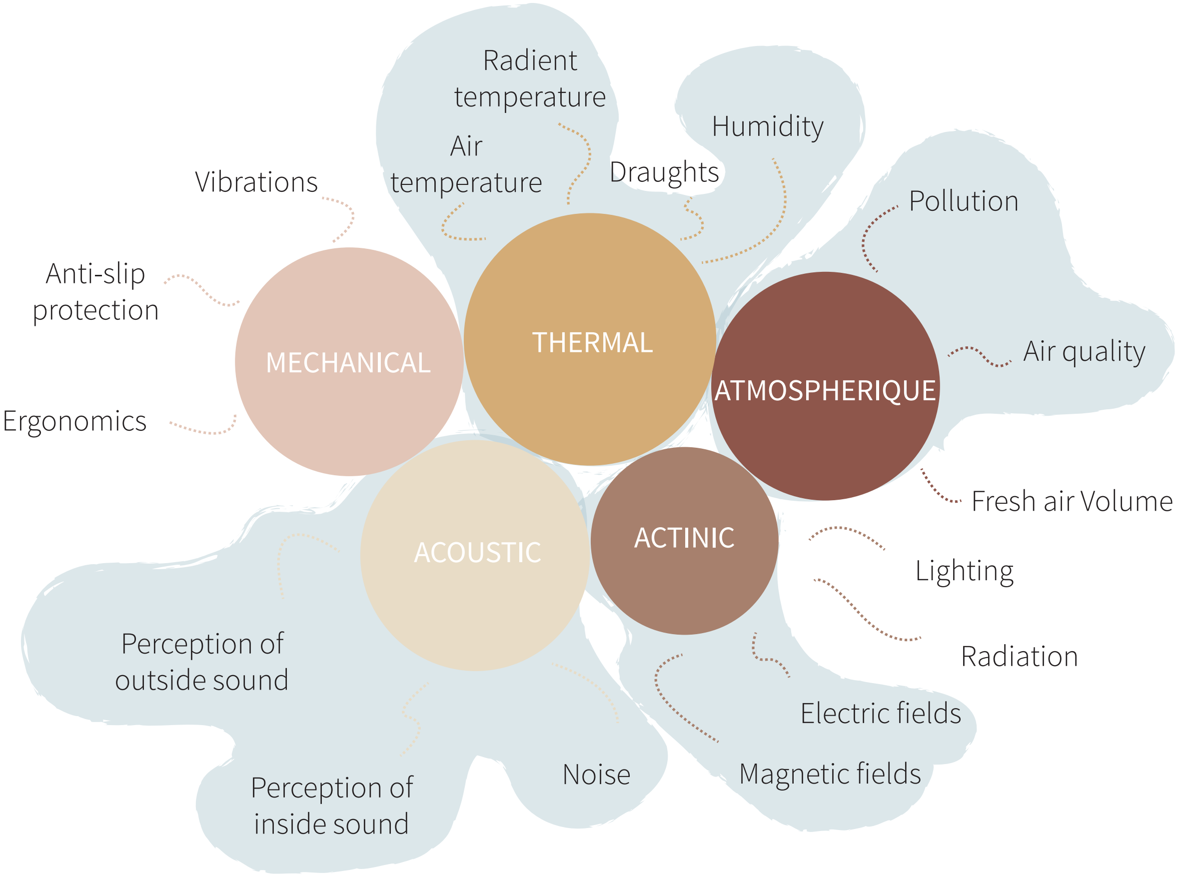


Figure 15. *Physical parameters of the indoor climate and domains of action of earth (By the Author, data from WHO)*

CLAY & INDOOR CLIMATE

THERMAL COMFORT

The most important vital parameter for a good indoor climate is thermal comfort, and it is also the one for which clay has the most positive effect. Thermal comfort depends on different parameters shown in *Figure 16*. (Nilsson P.-E., 2003) Humidity and radiant temperature can be effectively improved with the use of clay, and the strategies developed later in the testbed are based on these parameters. The air temperature depends on the internal and external heat gain and is therefore related to the insulation of the building and the heating system. Earth materials are poor insulators, however when mixed with fibers, they get better (Minke, G., 2009). Finally, the air speed is more dependent on the ventilation and the building's airtightness, on which clay do not have much effect.

Thermal comfort is difficult to describe and involves many parameters. The main condition for feeling comfortable is that the heat exchange between the body and its environment is balanced, *Figure 17*. Ole Fanger has developed a way to determine the optimum temperature for an environment by evaluating user satisfaction. His theory considers that "acceptable thermal comfort" is reached when there are no more than 20% dissatisfied and that in all case, it will always have about 6% dissatisfy, *Figure 19*. He explains that the thermal comfort zone depends not only on the temperature of a room but also on the metabolic heat and the insulation of people's clothes, *Figure 18*, which explains why it is such a subjective parameter and why it is difficult to satisfy everyone (Nilsson P.-E., 2003).

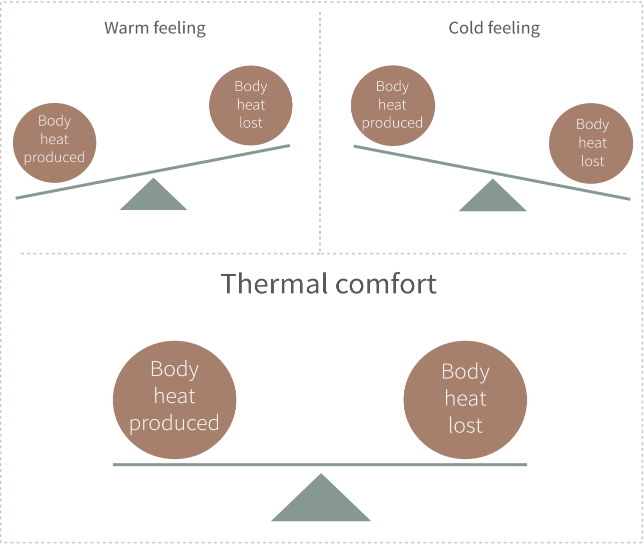


Figure 17. *Thermal balance (By the author)*

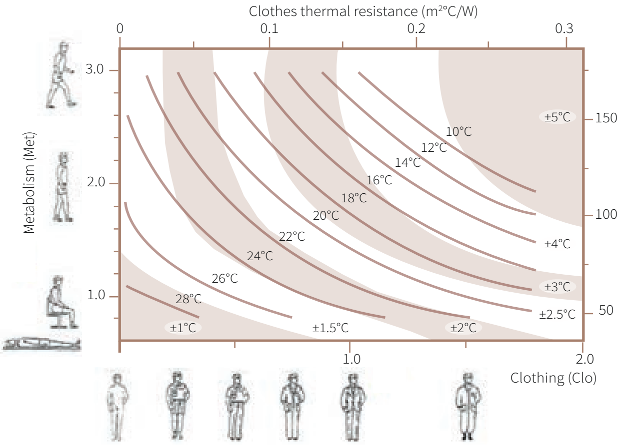


Figure 18. *Optimal operative temperature (Fanger, O., 1970)*

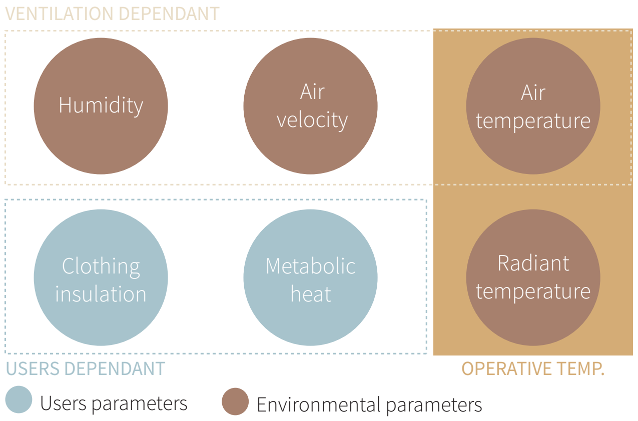


Figure 16. *Thermal comfort parameters (By the author, Data from Nilsson P.-E., 2003)*

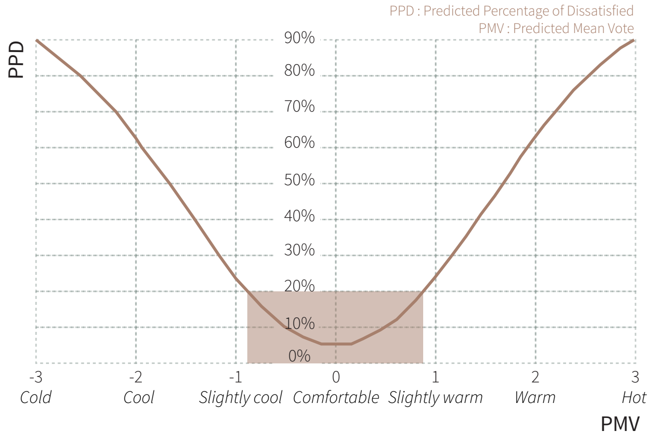


Figure 19. *Acceptable comfort zone (Fanger O., 1970)*

INSULATION PROPERTIES

The temperature of a building is a system affected by different parameters. For example, the indoor temperature increases or decreases depending on the outdoor climate. The heat transfer must be reduced to decrease the influence of the external environment and the energy loss, buildings envelops are therefore insulated. Different values to understand insulation are summarized in *Figure 20*. It shows the different parameters of the insulation and explains the relationship between the material's conductivity (λ) and its thermal transmittance (U) : the higher the conductivity of the material is, the less it insulates (Office fédéral de l'énergie, 2002).

Depending on the method and the use of the clay, it can reach different λ−values:

- In compressed materials (CEB, Rammed earth) the particles are close to each other which increases heat transfer. The conductivity of these materials turn around 1,1 to 1,4W/m.K (Röhlen, U., Ziegert, C.(2013). It is quite high, even though it is lower than a conventional reinforced concrete as shown in *Figure 21*. In cold climates the targeted U-value for walls is around 0.18 W/m^2.K, to reach such U-value without insulation a rammed earth wall should be 6.6m thick.
- Materials with incorporated fiber (light straw loam, cob...) have a lower conductivity thanks to the fibers. The usual λ is around 0.17W/m.K. In some case, the λ-value of certain light earth construction materials can be slightly lower than 0,1W/m.K, limit under which a materials is insulating (Röhlen, U., Ziegert, C.(2013).

THERMAL INERTIA

The structure and envelop of a building have a thermal inertia which contributes to the heating storage of the building. (Basecq, 2016) Thermal inertia is less often taken into account during the design of the building and it's indoor climate, although it is of significant importance. The thermal inertia of a material is its capacity to absorb heat (thermal effusivity), to store it (specific heat capacity) and to release it (thermal effusivity).

Thermal inertia increases with the density but it also depends on thermal conductivity of a material. Therefore, a 2000Kg/m^3 rammed earth wall normally has a higher thermal inertia than a light straw loam wall.

Thermal mass stores heat (or cold), and increases (or decreases) the radiant temperature of the surfaces (Reardon, C., 2013). This is why it is used as a passive strategy to keep a steady indoor temperature and to balance the operative temperature. There are two ways to use thermal inertia. The first one is to use the phase shift principle : mainly used in hot climates, it shifts the impact of accumulated daytime solar heat gains during the night. The heat then can be evacuated with a natural ventilation system using the outdoor coolness of the night, or it can be kept to heat up the room at night. In the same way the freshness accumulated at night is restored during the day, creating almost a micro-climate on the interior face of the walls (Reardon, C., 2013). In theory, this strategy, that use indirect solar heat gains could be used in cold climates during winter, to capture the heat from the sun during the day and restore that heat inside. The main obstacle

Name	Definition	Expression	Units
λ-Value	Amount of heat that goes through 1m^3 in one second with a difference of 1K between each side of the material	/	(W/m.K)
R-Value	Resistance to the heat transfer of a layer of materials. It depends on the thickness (e) and the conductivity λ(W/m.K) of a material	R = e / λ	(m^2.K/W)
U-Value	Thermal transmittance of a structure, or the flow of heat going through it.	U = 1 / R	(W/m^2.K)

Figure 20. Thermal units (By the author, Data from Office fédéral de l'énergie, 2002)

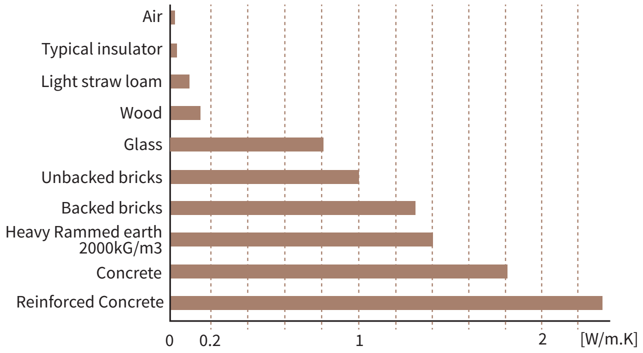


Figure 21. Lambda value of different materials (Adapted from R. Camponovo 2016, Building Thermal, HEPIA - Personal communication)

CLAY & INDOOR CLIMATE

for this to work in a cold context is the need for insulation, which stops the flow of heat into the wall. However, some design solutions such as the concept of solar or Trombe walls allow the use of indirect solar heat gains in a cold climate.

The second way to use thermal inertia is to capture direct solar heat gains and indoor heat gains on interior surfaces, *Figure 22*. Direct heat gains are related to the radiant gain when the sun hits the floor during the day while indoor heat gains, are linked to the activity in the building: people, heating system, appliances... The heat is transmitted to the surface by convection and conduction, the heat is stored in the material and released through radiation (Reardon, C. ,2013). In winter it reduced heat demands and improved thermal comfort.

To optimized the use of indoor heat gain, the thermal mass is very often used in synergy with a chimney or with integrated heating coils. The combination of an integrated heating system with thermal mass is really efficient and interesting, since it has a high emitting area such system can work with a lower heat temperature supply. Usually, in earthen constructions wall heating systems are described as more efficient than floor heating (Boltshauser, et al. ,2011). Indeed the floor is more suitable for storing direct solar heat gains and will partly lose this capacity with integrated heating coils.

To conclude on thermal mass, it is an important concept for the regulation of thermal comfort in cold climates in winter and many strategies can be implemented to use it. However, it must be well designed in order to avoid overheating in summer even in colder climate.

AIR HUMIDITY

The relative humidity of the air has a significant impact on health. It depends on the temperature and the vapor contained in the air. In Göteborg the average temperature from October to March is between -5 to +5°C. This leads to a significant temperature difference between indoors and outdoors. In addition, located in a coastal area Göteborg's average relative humidity is 80% between October and March, *Figure 24*. According to *Figure 23* and G. Minke, a fresh air at 0°C and 80% of relative humidity (average value in winter in Göteborg) that enters a room and is heated up to 20°C (room temperature target) undergoes a relative humidity drop to about 20% of water content.

A relative humidity lower than 30% increases the risk of affecting the mucous membrane of the organism leading to lower resistance to bacterias and viruses. On the contrary, if it is higher than 70% it could favor the formation of molds, pains and allergies as well as diseases in worse cases, *Figure 25*. Finally, the interval between 30% and 70% relative humidity has positive effects: it reduces the life of virus and bacterias as well as odors and increases the protection of the skin against various pathogens (Minke. G, 2009). This explains why ambient air are generally dry in Göteborg and why humidity level must be increased to avoid infection or disease.

A solution to balance the relative humidity of a room is to use the capacity of some materials to exchange humidity until it reaches an equilibrium with the room. Thanks to its structure clay is one of them because it can capture and release humidity.

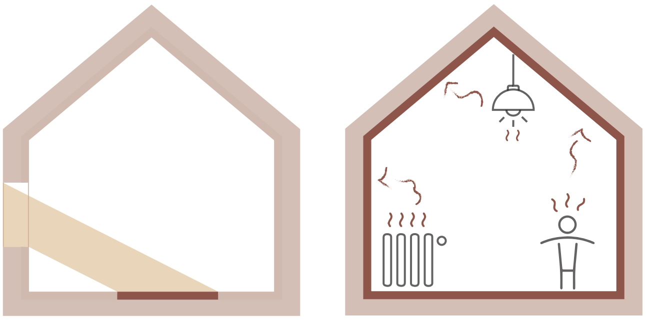


Figure 22. *Sources of heat stored by thermal mass : on the left direct solar heat gains, on the right indoor heat gains. (By the author)*

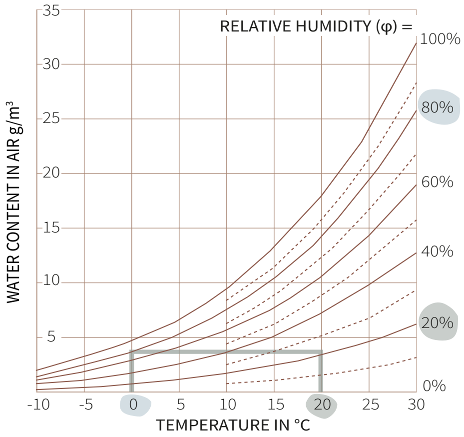


Figure 23. *Relative humidity depending on the temperature and the water content in the air (Minke, G, 2009)*

HYGROMETRIC PROPERTIES

Because clay is porous and has the ability to hold water in its lamellas (see p.18), it can absorb moisture from the air when it is too wet and desorb it when it's too dry. This absorbed water does not affect the state of the material (see p. 19).
There are two measurable variables to determine a material's ability to have a humidity balancing effect (Minke. G, 2009):

- The equilibrium moisture content
- The speed of the absorption/desorption process.

The equilibrium moisture content is the maximum amount of water that a material can contain under a given relative humidity and temperature context. Some materials can absorb or release more water than others. For example under 80% humidity, a loam brick can store up to 7% of its mass of water (Minke, G. 2009). In *Figure 26* we can see that the maximum amount of water absorbed is higher for the clayey loam plaster (2, 60g/m^2) than for the gypsum (7, 45g/m^2). It also shows that the addition of fibers in the materials slightly increases the absorption capacity (clayey loam plaster, 2, versus loam plaster with coconut fiber, 3). For earth, the implementation technique is important but also the type of clay and the mixture : three layers clays can absorb more humidity than two layers clays because they have larger specific surfaces (Röhlen, U. et all, 2013). Some kind of smectite clay can contain 15% of water, while kaolinite clay can only receive 1% of its mass (Minke. G, 2009). Previously, Illite was described as a three layer clay and has therefore good properties for humidity regulation.

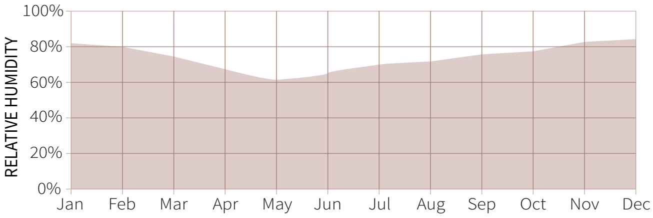


Figure 24. *Average relative humidity in Göteborg in 2019 (adapted from www.weather-and-climate.com 2019)*

In addition, it takes different time for each material to reach their equilibrium. For the humidity balancing effect the speed of the absorption/desorption is also very important : the building elements must react as quickly as possible in the event of a change in relative humidity in order to maintain a good humidity and comfort level. *Figure 26* also shows the speed of absorption (and desorption) of a 15mm thick interior wall sample for different materials. It points out that wood (4 and 5) is almost as good for absorption as clayey loam plaster (3) but slower to reach the maximum value. It is therefore less advantageous to use wood for a rapid regulation. Another study also shows that only the two first centimeters of materials absorb humidity within the first 24 hours. (Minke, G., 2009) Therefore, a thin layer of the material would be sufficient for effective humidity regulation. This highlights the relevance of applying clay plasters to regulate humidity, which is commonly used in renovation contexts.

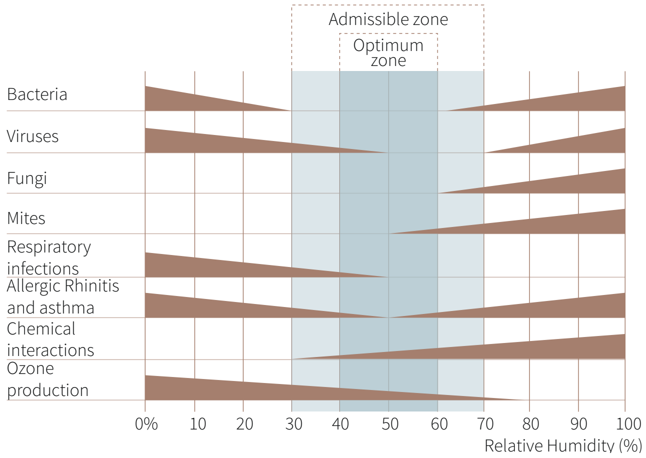


Figure 25. *Humidity and health (Adapted from Arundel et al., 1985)*

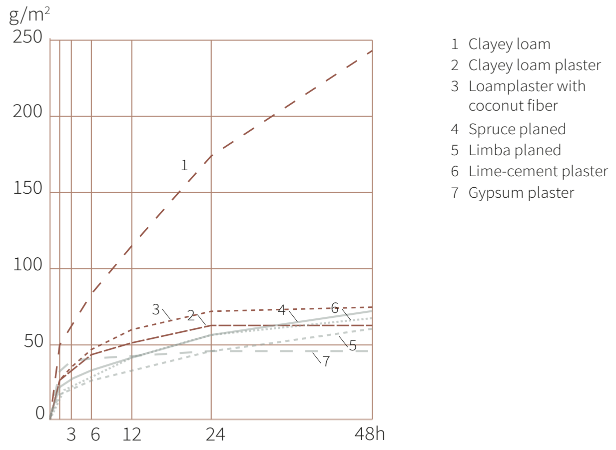


Figure 26. *Absorption curves of 15mm thick samples, at 21°C after a rise in humidity from 30% to 70%. (adapted from Minke G., 2009)*

CLAY & INDOOR CLIMATE

AIR QUALITY

Indoor Air Quality (IAQ) is defined by how the air is perceived by a person in a room and its effect on the body. It depends on the humidity level, previously developed, but also on odors or volatile organic components (VOCs). Unlike odors, those harmful particles in the air cannot be felt at first. They are due to human activities inside but are also released by the materials or related to ventilation. The impact of particles on health depends on their nature, quantity and time of exposure (Nilsson P.-E., 2003). They can have short and long-term effects of various kinds (from simple headache, to asthma, cancer or reproductive system disorder).

In this regards, earth is a natural material which does not create any VOCs. In addition, clay materials are not electrostatic, thus avoiding the storage of dust which often contributes to indoor air pollution. According to Gernot Minke, clay improves indoor air purification by capturing and absorbing pollutants, however it has not been scientifically proven yet. (Minke, G. 2009).

Finally, most building materials emit a certain amount of radon, but clay emits a very low level. Radon is a radioactive gas that can mainly be inhaled and is identified as a major cause of lung cancer. According to a study conducted by the OECD in 1979, a fired clay brick contains 5.0 becquerel/kg.h while natural gypsum contains 25.2 becquerel/kg.h and porous concrete 18.0 becquerel/kg.h. Thus, clay materials discharges lower amount of radon than other materials. (Minke, G., 2009)

ACOUSTIC ENVIRONMENT

The acoustic environment of a building is very important and takes in consideration two different aspect (Nilsson P.-E., 2003) :

- Avoiding unwanted sound (phonic insulation)
- Keeping wanted sound (room acoustic).

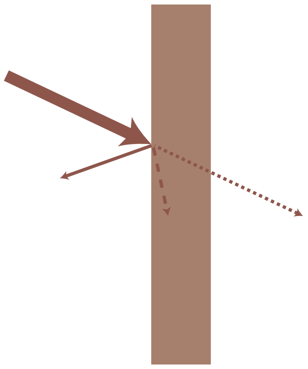
Noise is a wave that travels through the free air and interacts with surrounding surfaces. These surfaces can absorb or reflect as well as transmit sound, *Figure 28*. Sound insulation is intended to protect users from disturbing noise which can lead to health or mental health problems and must be avoided (Nilsson P.-E., 2003). It is defined by the Weighted Sound Reduction Index (Rw) and expressed in decibels. There are three main sources of unwanted sounds :

- Noises that enter the building
- Noises that are transmitted into the building
- Noises from building services.

The room acoustic, on the other hand, aims to make sound intelligible and suitable for the purpose of the room. The acoustic of a room is made of several parameters : the absorption coefficient of the materials (α Sabine) but also the shape, the volume and the furniture of the room. All together impact and change the noise perception. (Nilsson P.-E., 2003)

PM	Cooking stoves, fireplaces, smoking...
SO_2	Cooking stoves, fireplaces, outdoor air...
NO_2	Cooking stoves, fireplaces, outdoor air...
CO	Cooking stoves, fireplaces, outdoor air...
Ozone	Air cleaning device , outdoor air
VOCs	Building materials, paint and solvents, clothing, air fresheners, incense, certain plants ...
Radon	Exuded from underground and contains is some materials, such as stone and concrete
Bioclіgocal air pollutants	Pets, human, dust mites...

Figure 27. *Sources of indoor air pollutants (adapted from D. Y. C. Leung, 2015)*



▬ Incident energy	Direct noise source
— Reflected energy	Depends on the absorption coefficient ($0< \alpha <1$). If $\alpha = 0$, 100% of the sound is reflected
- - - - Absorbed energy	Depends on the absorption coefficient ($0< \alpha <1$). If $\alpha = 1$, 100% of the sound is absorbed
········ Transmitted energy	Depends on the accoustic attenuation of the material's Rw value, expressed in dB

Figure 28. *Sound behavior (Author)*

ACOUSTIC PROPERTIES

First, regarding the room acoustic, earthen rooms are often referred as being "cozy". It is difficult to find quantitative studies of the impact of earth on the reverberation of a room. However, it seems that denser materials reflect more sound energy than lighter ones (Hall, M.-R., Lindsay, R et all, 2012) and we know that earth is a dense material (rammed earth, CEB). So why is it so good for acoustic perception ? According to Dominique Gauzin-Müller, 1m^3 of earth contains around 10^{17} grains, increasing the porosity and creating a grainy surfaces (Gauzin-Müller D. 2020, november). Thanks to its texture the surface increases frictional forces and decays the sound quicker, which could explain why earth gives this acoustic effect. It is possible to assume that light earth materials would have better absorption properties than compressed earth materials, since fiber panels are often used for sound improvement.

The surface texture is not the only thing that can affect the reverberation of a room : the shape can also provide improvement and earthen materials allow a great flexibility in the design of the surface, such as shaped bricks. Some example are developed in the chapter "Catalog".

Finally, about the sound insulation, the more dense the materials, the less it transmits airborne noise. We have seen that the density of clay material is often high and therefore very good in that area, but it also depends on the frequency of the noise.

ACTINIC ENVIRONMENT

The actinic environment is related to the exposure to a radiant energy such as light and the electrical or magnetic field. Light will not be studied because it is not directly related to earth properties. Although no study has clearly established the link between electromagnetic radiation and several health problems such as cancer, they are subject of much controversy. Indeed, some subjects describe disturbance they undergo because of such radiation and try to avoid this "electro-smug".

ACTINIC PROPERTIES

It seems that earthen construction can reduce or absorb the electromagnetic radiation that enters the building and create a shelter against electro-smug. There is not much studies on the subject, and it would be very interesting to develop it further in another research study. However, according to Thomas Kamm, it is difficult to get a cell phone signal in the Rauch house and even impossible in the entrance and the staircase (Boltshauser, R., Kapfinger O., et al. 2011). Finally, *Figure 30* shows how high frequency radiations are reduced by different building materials. The higher the frequency in GHz, the more earth materials block them. In general, we can see that earthen material have a better damping effect than other materials.

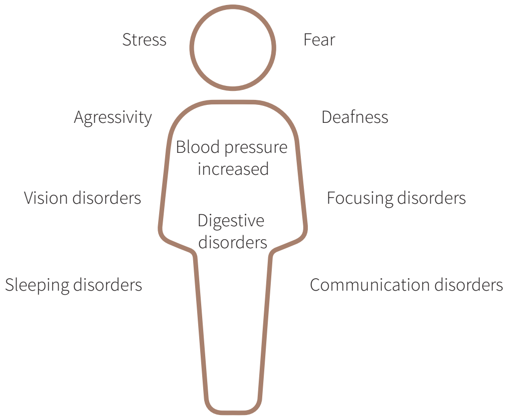


Figure 29. *Effect of the noise on the body (By the author)*

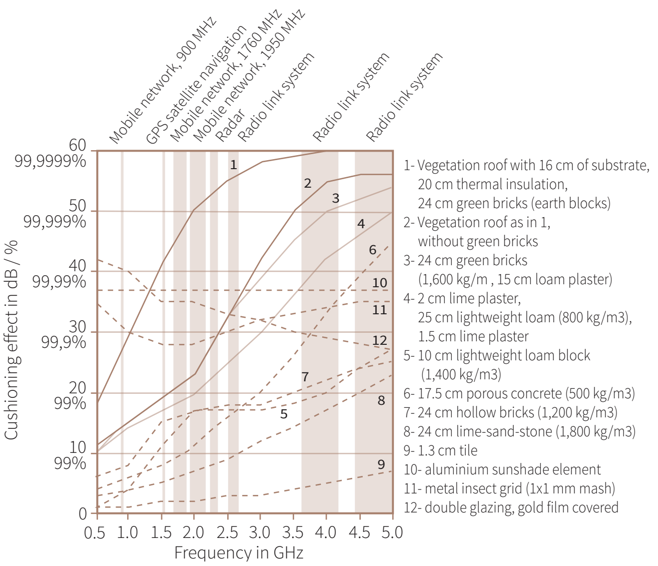


Figure 30. *Reduction of electromagnetic radiation (adapted from Minke G. 2009)*

CLAY & INDOOR CLIMATE

> “
>
> *There is no other material which maintains the perfect indoor humidity and absorbs smells; which creates pleasant acoustics; which can bear structural load and act as a thermal mass.*
>
> - A. Heringer, L.,B. Howe & M. Rauch - in *Upscaling earth*
>
> ”

CONCLUSION

This chapter described in more depth the properties of clay and how it interacts with its environment to provide qualitative indoor climate. *Figure 31* shows the links established between the five identified indoor climate environments and the associated properties of earth materials that have been described in this chapter. This is a summary in order to clarify which properties act on which parameters.

It is difficult to clearly assess earthen materials and give a precise value to each of the parameters because it depends on the composition of the earth, the compression and thus the techniques used. When one earthen technique is very good for one parameter, another technique is better for another parameter. This variety of use allows the flexibility of raw clay : it can be implemented in many different ways and therefore easily adapted according to the needs. It is then relevant to define the use not only on the basis of the architectural concept but also on passive strategies. For example, if the objective is to bring thermal mass to a light wooden structure, the choice should be on a dense earth technique such as rammed earth or CEB. On the other hand, if there is a need for insulation improvement, a mixture of straw and earth seems more appropriate. It all depends on the benefits sought by the use of earth as a material. In any case, when earth is used intelligently, it improves the indoor climate and the health of the occupants of the building.

In addition to these physical properties, Canadian researchers found that being in contact with earth can increase happiness and well being. They identified that the bacteria “Mycobacterium vaccae” naturally present in the soil, stimulates the production of Serotonine (happiness hormones) in the body which helps to reduce the level of stress, and to fight against depression and inflammatory diseases. Rob Knight said : “Human ancestors used to encounter these microorganisms in abundance every day, but modern life doesn’t facilitate those interaction”. The report states “A lack of exposure to these organism is thought to contribute to the current epidemic of inflammatory disease in modern urban society” (University of Colorado Boulder, 2016)

Thus, building more with earth would promote the reconnection between modern society and these micro-organisms, participating in the improvement of life.

This is one more reason to bring earth back to building.

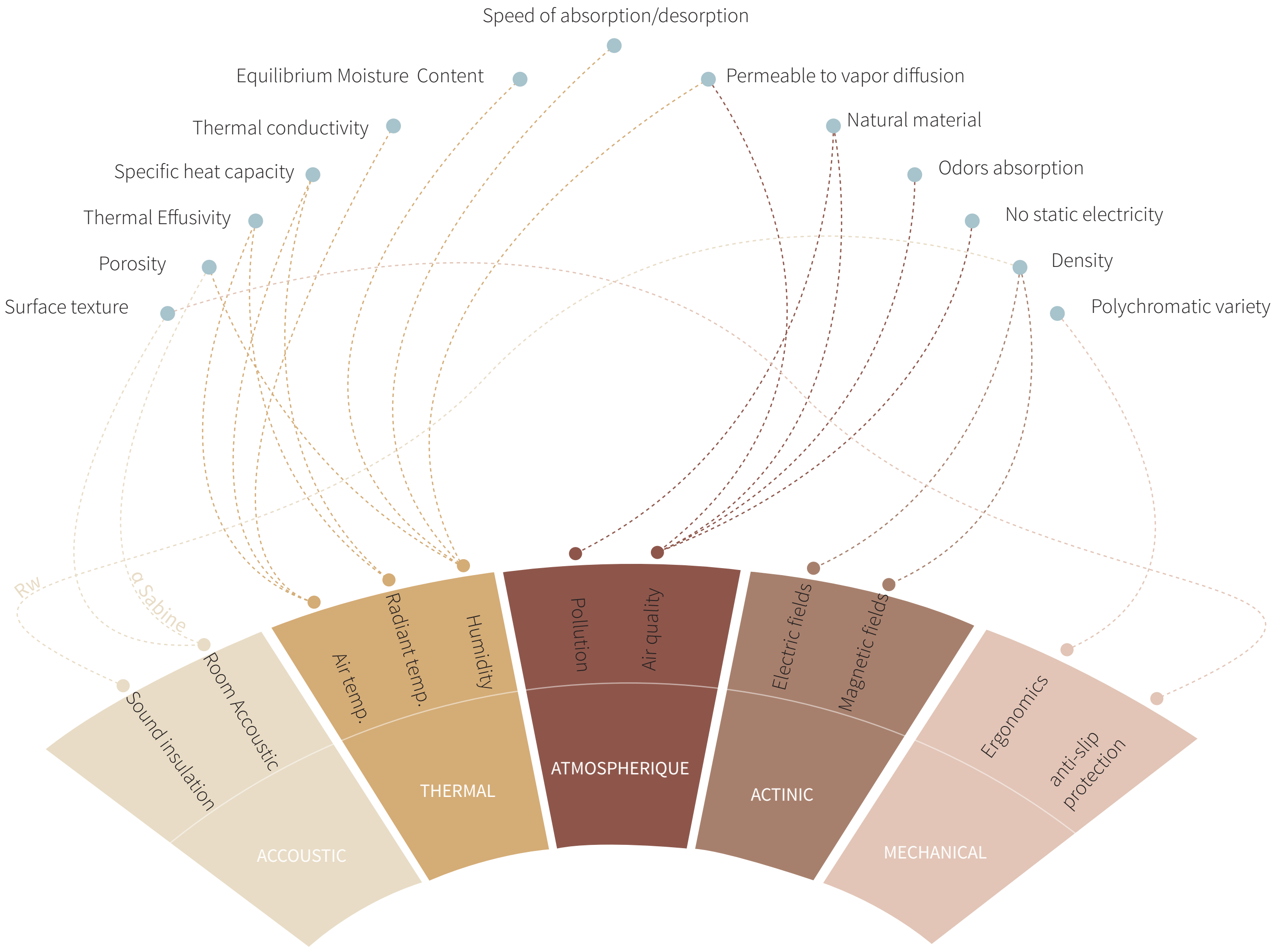


Figure 31. *Indoor climate parameters and related earth properties (By the author)*

CLAY & SUSTAINABILITY

> “*Concrete or brick buildings require ten to twenty more energy for production, precessing and transport than clay. In terms of sustainability, due to the low level of primary energy and its unlimited recyclability clay is even more efficient than wood.*
>
> - Otto Kapfinger - In *Haus Rauch*”

CIRCULAR ECONOMY

In all fields, the actual production, consumption, and disposal of goods follow a linear pattern. The circular model is considered as a possible solution allowing better use of resources for more reasonable consumption and thus creating a sustainable future. The main purpose of the circular economy is very well explained by the expression “Cradle-to-Cradle”: in this concept, nothing is a waste but everything is a resource, *Figure 32* (McDonough, 2017). The building sector must adapt to this. Many solutions and possibilities exist, such as the design for disassembly, which makes possible to reuse some parts of a building or to recycle other parts. Clay, on the other hand, does not need to be designed in a specific way to have a second (third or umpteenth) life. This is one of its natural properties: as long as it is not fired above 400°C, the binding properties are reversible and time does not alter any property of the material (Minke, G. 2009). Therefore, earth can be reused endlessly or returned to the ground after use without introducing new energy into the process.

On the other hand, this is not true if earth is stabilized (with cement or lime for example) and this is why it is important to use earth as naturally as possible, within its limits of use.

LIFE CYCLE ASSESSMENT

Earth material has a very low impact in all its LCA (Life Cycle Assessment). Indeed, the excavated material can be used directly as a building material (Rammed earth, cob, plaster...), or it can go through a production step to transform the raw material into a building material, *Figure 33* (CEB, Adobe, prefabricated rammed earth...). Generally, the transformation of a raw material into a building material is the most energy-consuming step in the manufacturing process of usual building materials, but for earth, when it is used in its raw state (unfired and non-stabilized) there is no transformation but only a modeling step. It mainly consists of shaping elements by compression or extrusion and letting them dry naturally until it is ready to be used. This is why its implementation consumes little energy and emits little emissions compared to usual material.

The production step can be remote or on site and therefore there is not necessarily a transportation step.

At the end of its life, the building can be demolished and transformed into a new material for a second life. It can also be crushed and left in place since it is natural.

In the process, the steps that still produce CO_2 emissions and need energy are the excavation, transportation,construction and demolition but it depends on what kind of engine is used. It is starting to be possible to use electric and fossil free machines to avoid emissions (Provided that the electricity is green).

FOSSIL FREE & CARBON NEUTRAL MATERIAL

It fits in all actual discourses : it does not create material shortage since it can be reused, and does not require any specific transformation to be implemented, releasing no or very low amounts of CO_2 emissions with low energy needs. At a time when the embodied energy of a building accounts for nearly 50% of its total energy consumption over its lifetime, it is not insignificant and really relevant to consider.

To conclude, clay is a fossil-free material that hardly generates any emissions, so it is relevant to apply it to a project such as the “Hoppet project” because it fits the project’s philosophy.

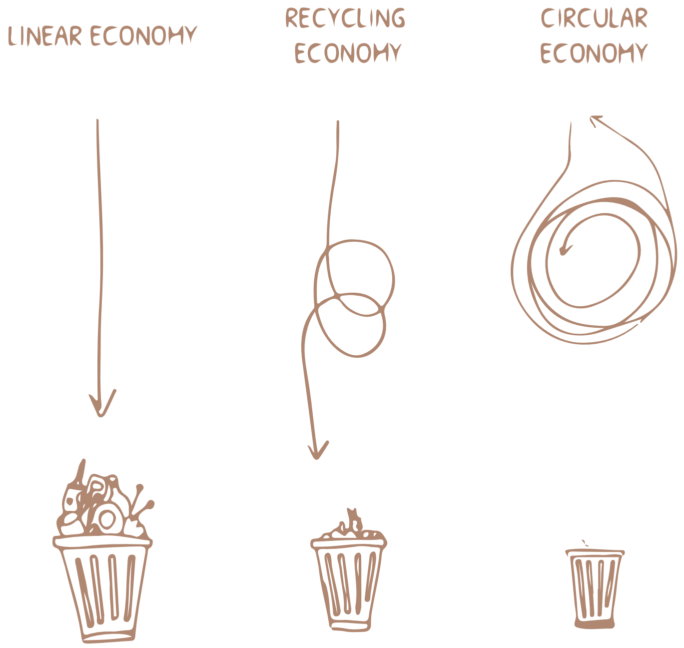


Figure 32. *From linear to circular (Adapted from Circular Flanders, 2017)*

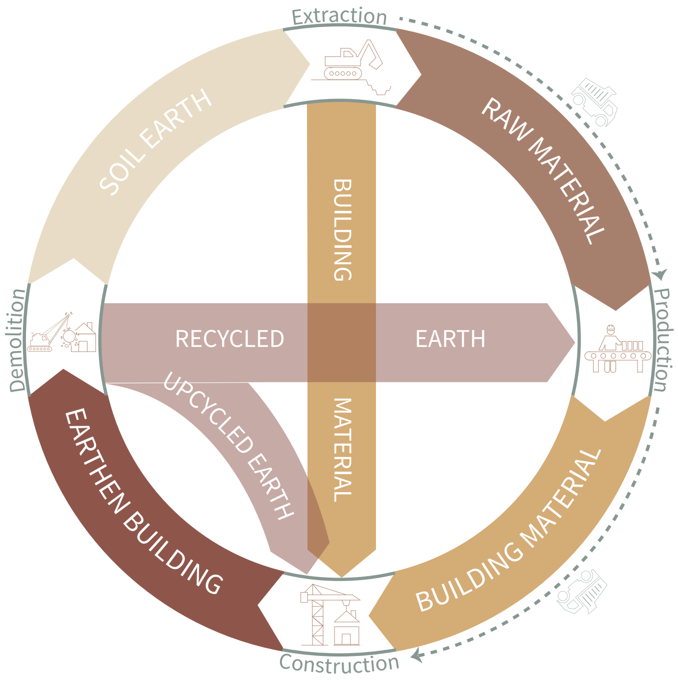


Figure 33. *Life Cycle of an earthen material (By the Author)*

3

Clay in practice

In this chapter, results and photos of field tests are presented to understand and present the local clay and how it reacts. The second part of the chapter focuses on several case studies to show the clay material in application at different scales and using different techniques. The analysis of each case mainly highlights indoor climate improvements by the use of clay.

FIELD TESTS

INTRODUCTION

Field tests have been carried out to understand the properties and reactions of clay in different situations. The results are illustrated here. The clay used comes from the excavation for the creation of the Marieholmstunneln, under the Göta älv. More information on the procedures, expected results and their interpretation are presented in appendix B. These tests are commonly described and used in literature to evaluate clay quality. The first part of the test aims to understand the clay content of the sample, while the second part aims to test different types of mixtures (with sand and salt) too see how it affects the reaction and properties of the material in each different test.

Image 5. Visual test (Pictures and test by the author)

< VISUAL TEST

Grey clay, with dry and stiff aggregates (which are not gravel), difficult to crush by hand (upper picture), indicates a significant amount of clay. The clay was crushed and sieved for the next step, nothing was removed from the material, it reveals a very fine earth without gravel (bottom picture).

SMELL TEST>

Very little scent, almost salty.

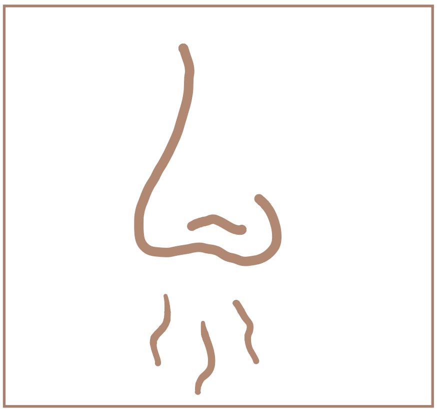


Image 6. Sedimentation test (Picture and test by the author)

<SEDIMENTATION TEST

The composition of earth is about 36/37% clay, 36/37% silt and 25% very small grains of sand. A few organic compounds were floating at the top of the bottle.

WASHING HAND >

After the washing process, only a small amount of aggregates remained, mainly sand with small orange/red gravels.

Image 7. Washing test (Picture and test by the Author)

<DRY HAND TEST

Smooth sensation, slightly floury with a few small grain.

<HUMID HAND TEST

The bigger aggregate took time to become smooth, due to an important amount of clay.

CUTTING TEST>

The surface is mostly shining and partly dull, indicating a high content of clay.

Image 8. Cutting test (Picture and test by the author)

BALL DROPPING

Pure clay ball with 23% of water (A-3) does not flatten after falling and is very strong. The cohesion of that mix is too high and the addition of sand would be better (Minke, G., 2009). Indeed, when the same proportion of water is added to the sand and clay mixture the ball flattens very slightly, it is more suitable (C-3). Salt has no significant effect on pure clay, although the ball is a little softer (B-3). On the other hand, salt seems to have a significant effect on the clay and sand mix : with only 17% of water (D-1) cohesion is higher than in the previous mixture and good cohesion is reached for 20% of water (D-2) At 23% of water it is too plastic and too deformed after the fall to be good (D-3).

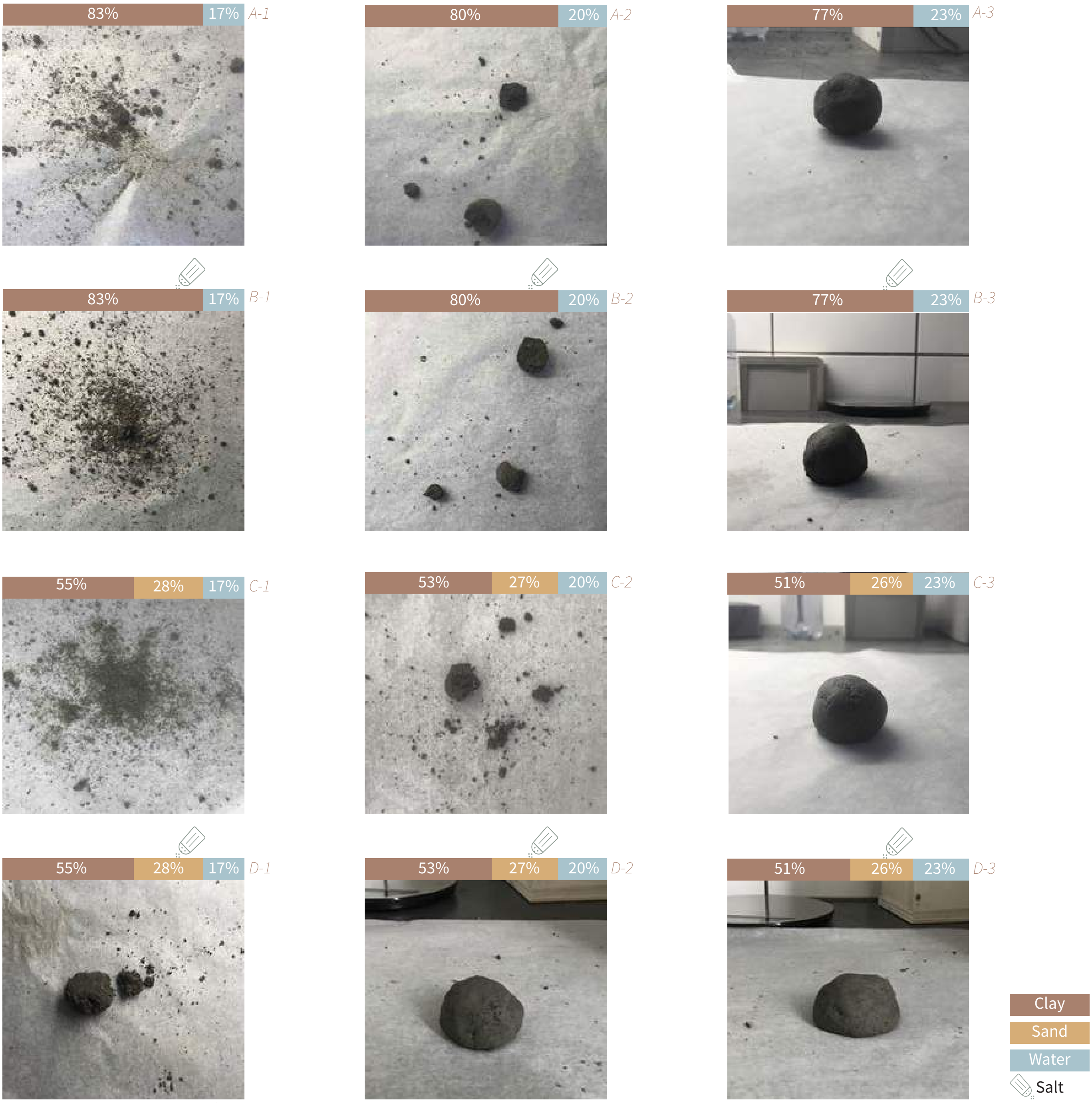


Image 9. *Drop test with different mixtures ((Pictures and tests by the author))*

FIELD TESTS

SHRINKAGE TEST

This result outlines that the sand decreases the shrinkage ratio of the samples. Indeed, pure clay has a shrinkage ratio of 7% (A), which is very high but logical. Adding sand to the mixture halves this effect (C). Adding salt does not impact the shrinking rate of the sample with sand (D), but it improves it a little for the pure clay sample (B).

BALL IN WATER

The first thing to emphasize is that the salt protects the ball from dislocation in water. Indeed, the pure clay sample begins to disintegrate after only two hours (A-3), whereas with salt, it does not move even after 13h in water (B-4). The sand also seems to have a positive effect on the time it takes to collapse. Therefore the time scale is not the same for the different mixes : the ball of clay and salt start to collapse after 13 hours (C-3).

Image 10. Shrinkage test with different mixtures (Pictures and tests by the author)

Image 11. Ball drop in water with different mixtures (Pictures and tests by the author)

COHESION TEST

This test compares the different mixtures on the cohesion and elasticity properties. Pictures are from a video and chronological. It is not a very precise method, but the test has been performed several times, and the samples with sand always fall done first. It can therefore be concluded that sand decrease the resistance of the sample. And it makes sense because it decreases the proportion of clay that is responsible for the bonding effect of the sample. On the other hand, salt does not seem to have an effect on the cohesion.

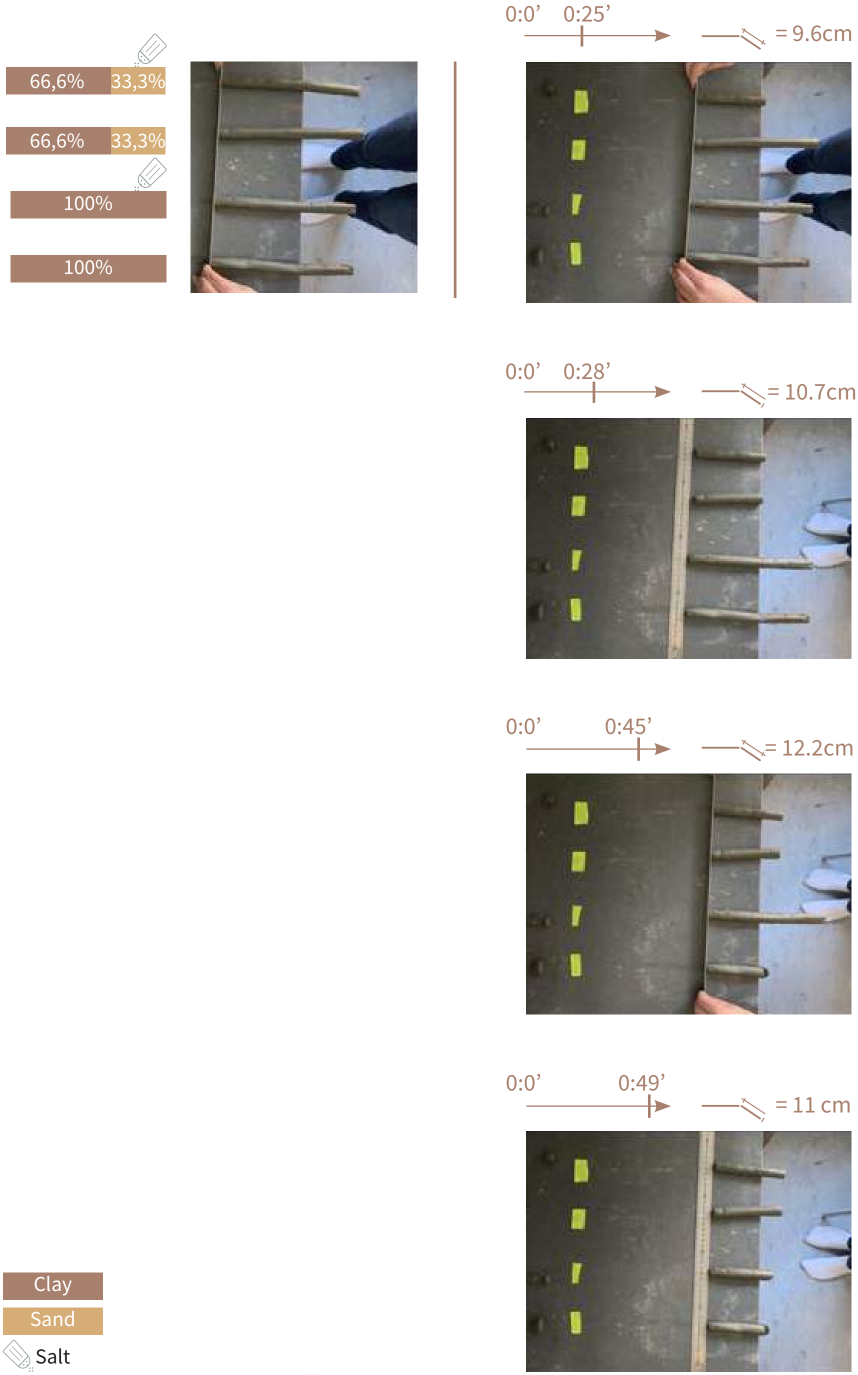


Image 12. *Cohesion test with different mixtures (Pictures and tests by the author)*

TEST CONCLUSION

From the result of the first part, we can conclude that the local clay is composed of a high clay content and can be described as “Clay” or “Clay loam” according to the classification shown in Figure 9 on page 19. It is suitable to be used for building in a first stage of analysis.

In addition, it is a very fine kind of earth with no stones or gravel and in earth construction it is particularly suitable for Cob, and plaster (Fontaine & Anger, 2009).

However, because it has a high clay content, it would need an addition of sand to reduce the shrinkage, especially when working with monolithic constructions. Yet, this quantity of sand must be evaluated with precision : too much sand and the cohesion strength would be too low; Not enough and the shrinkage would be too high.

In a second part, the test also describes the effect of adding salt for water protection, and it would be interesting to study this further. Perhaps this can lead to an earthen material more suitable for room exposed to water or even be more weather resistant. Many additions can be made to improve the properties of an earth material.

The choice was made to focus the tests on the addition of salt and sand. This choice was done according to the notion of quick clay, described previously on page 20, and the particular link between Göteborg clay and salt.

CASE STUDIES

INTRODUCTION

Clay can be used in different ways. The most common are explored here regarding their benefits on the indoor climate but also other criteria that are relevant in all cases such as the economical aspect. The following case studies consist of an analysis of the use of earth in the building, with an evaluation of the techniques used. Most of the projects will be develop briefly, while the study of the Rauch House, entirely made of earth, will be an in-depth analysis.

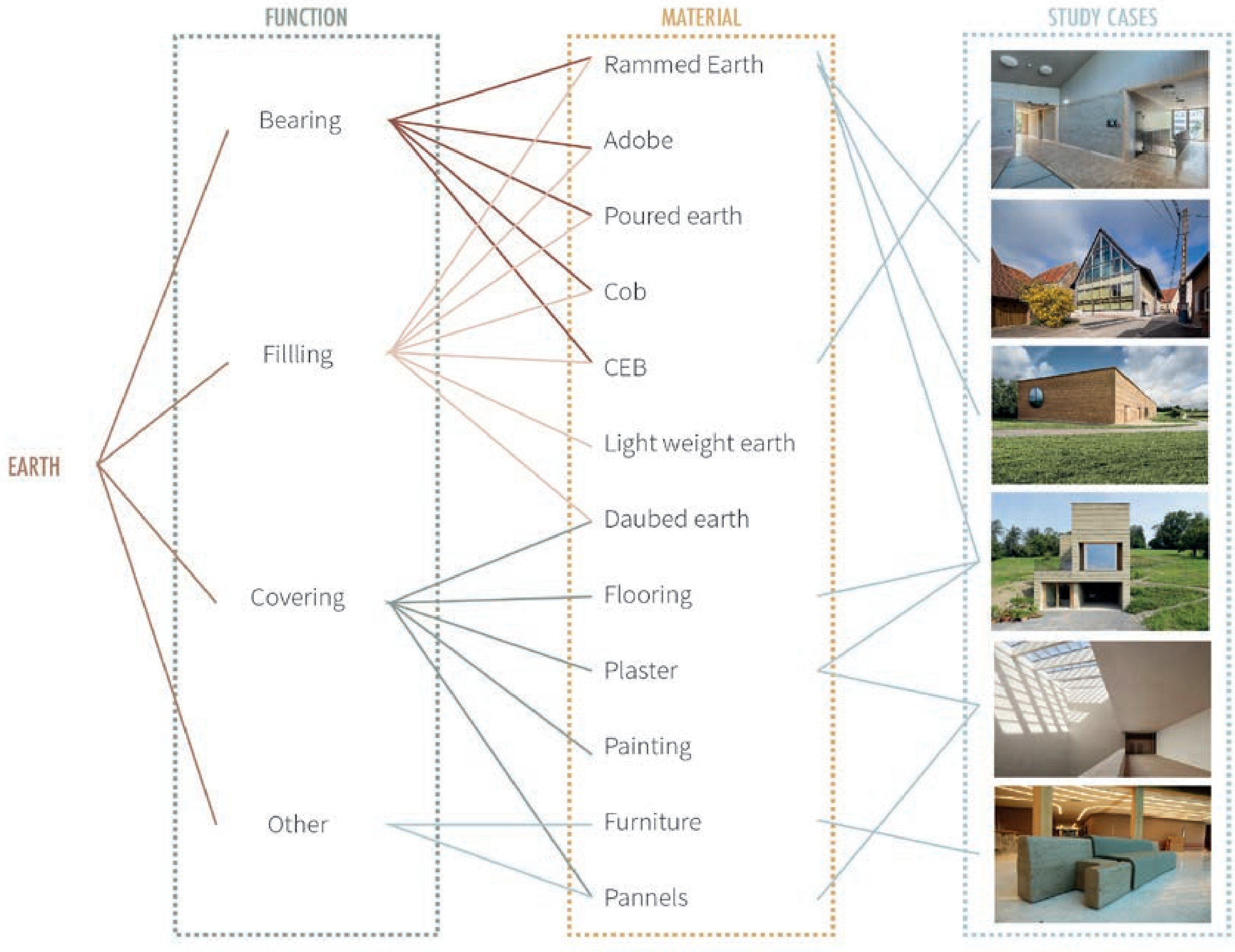


Figure 34. *Study cases introduction (By the author, reference for each photo on the respective case studies pages)*

CURVE

PROJECT ID

Location : Saint-Denis (FR)
Designer : RFStudio
Completion year : 2020
Function : Office building reception
Earth techniques : Rammed earth
Earthen work : Amàco

Image 13. *Curves (©Amàco)*

EARTH FUNCTIONS

☐ Load-bearing ☐ Filling ☐ Covering ■ Other

In this project, the earth is used on a small scale: for the furniture. For this office building reception hall, six benches were realized in rammed earth. The shape is build around a lost formwork, and therefore the thickness of the rammed earth is only 7 cm. It makes the furniture lighter and easier to move. It would be interesting to perform measures with and without the benches to find out if it can effectively influence indoor climate. It is interesting to see that earth can also be implemented in such a situation. (Amàco 2020)

ENHANCED COMFORT QUALITY*

●●○○ *Thermal mass*
●○○○ *Temperature stability*
●○○○ *Moisture regulation*
●○○○ *Acoustic insulation*
●●○○ *Room acoustic*
○○○○ *Passive heating*
○○○○ *Actinic*

**Subjective analysis based on literature of the project and on the theoretical part.*

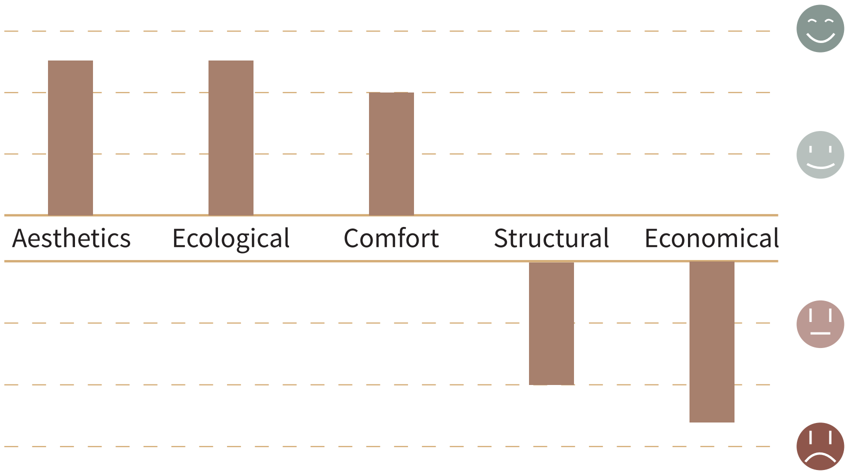


Figure 35. *Earth furniture Evaluation (By the author*)*

LE PAVILLON GEISENDORF

PROJECT ID

Location : Geneva (CH)
Architect : David Reffo
Completion year : 2018
Function : Scholar equipment
Earth techniques :
Compressed Earth Bricks
Earthen work :
TERRABLOC

Image 14. *Corridor in the pavillon Geisendorf (©Didier Jordan)*

EARTH FUNCTIONS

▨	☐	☐	☐
Load-bearing	Filling	Covering	Other

This two floors project is supported by a load-bearing structure in Compressed Earth Blocks CEB (intra-muros load-bearing structure, around the atrium). This structure carries the slab together with a wooden structure (located only on the peripheral walls). It is therefore not a matter of filling but of a load bearing function. The CEB are made with the earth from the excavated site. Due to the lack of standards, the design had to be anticipated four years before the start of the construction in order to perform soil tests, prototype and strength tests. The choice of the CEB was made to provide thermal mass to the wood structure (Fernandez R. , 2021, Personal communication).

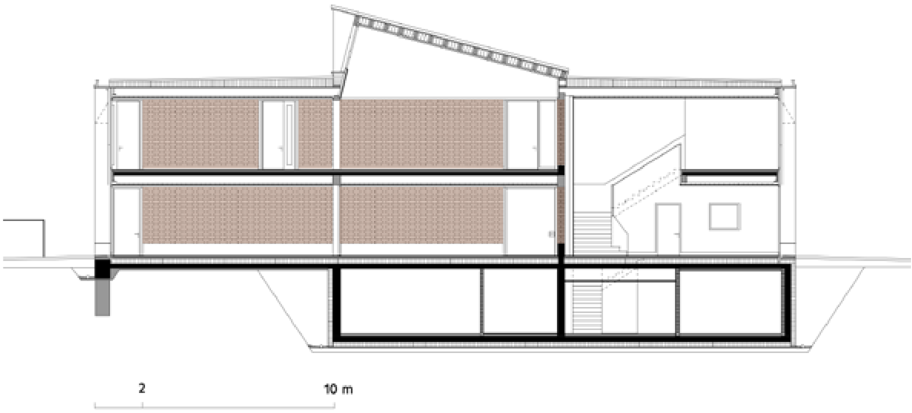


Figure 36. *Project section (D. Reffo Architecte)*

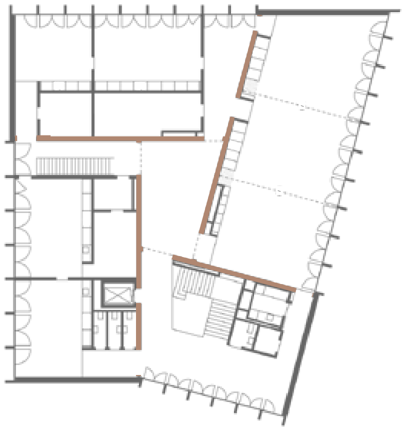


Figure 37. Project section (D. Reffo Architecte)

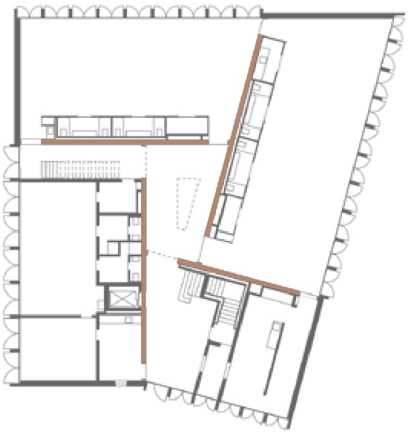


Figure 38. Project section (D. Reffo Architecte)

PROPERTIES EVALUATION - CEB

Information gathered during an interview with Mr Rodrigo Fernandez, from Terrabloc

Aesthetics - "naked material" with strong materiality and texture that correspond to the architectural trends.

Ecological - According to Rodrigo Fernandez, the ecological aspect must be a compromise between the environmental impact and longevity. CEB contains 4% cement, (when 5%, it accounts for 30% of the gray energy of the product). Without it, the walls would be more expensive and would need a greater quantity of raw material to be load bearing (40% thicker), this makes it possible to reduce the natural and mechanical erosion. In that case, using the right amount of cement makes the project more rational and the product remains with a very low environmental impact .

Comfort - Synergetic behavior between wood and the thermal mass of the earth. Both work well together because the CEB can absorb residual water from the wood. It also regulates the humidity level of the building by catching excessive humidity and releasing it if the room dries up. In addition, hallways and atriums can be noisy, thus CEB here decreases the resonance of the room

Structural - the structural aspect of CEB should not be seen as the future of the material. Up to two floors it can work, but for higher buildings it would not be rational. It is better to use it in a mixed structure to take advantage of the properties of both materials (wood and CEB for instance).

Economic - It is more expensive (≈ +30%) than other materials at the moment due to the actual low volume production due to the low demand .

ENHANCED COMFORT QUALITY*

●●●● *Thermal mass*
●●●○ *Temperature stability*
●●○○ *Moisture regulation*
●●●○ *Acoustic insulation*
●●○○ *Room acoustic*
○○○○ *Passive heating*
●○○○ *Actinic*

**Subjective analysis based on literature of the project, interview and on the theoretical part.*

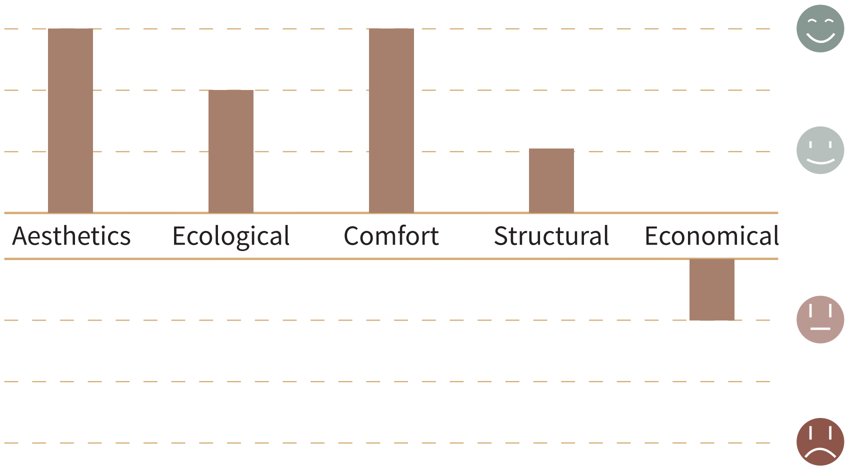


Figure 39. Compressed Earth Brick Evaluation (By the author*)

MAISON KOEPPEL EXTENSION

PROJECT ID

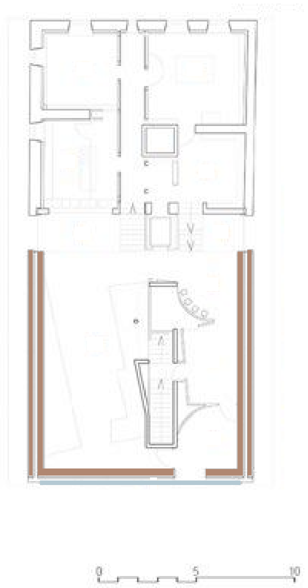
Location : Dehlingen (FR)
Architect : Nunc
Completion year : 2014
Function : Museum
Earth techniques :
Load bearing rammed earth (rammed on site), pre-fabricated rammed earth and solar wall

Image 15. *Centre d'interprétation du patrimoine archéologique, Nunc architectes (© Luc Boegly)*

EARTH FUNCTIONS

▨ Load-bearing
☐ Filling
☐ Covering
☐ Other

The project is the extension of an old traditional farm. The lateral load bearing walls consist of a double layer of rammed earth with insulation in between. They support the three floors of the building. The wall facing the interior, load-bearing, is rammed on site while the exterior skin is prefabricated and only self supporting. The south wall is a solar facade (Load-bearing earth wall combined with a glass facade). During the cool autumn, winter and spring days it preheats the fresh air distributed in the building. During the coldest days, the shaft is closed and the wall transfers the heat inside thanks to its thermal mass. Finally in summer, an outlet in the roof ventilates the solar wall to prevent overheating. (*Figure 42)*



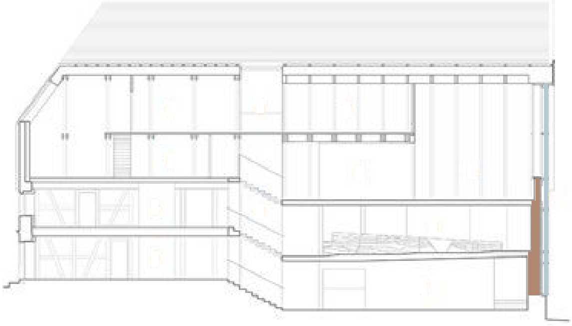


Figure 40. *First plan (Nunc Alsace Architectes)*
Figure 41. *Section (Nunc Alsace Architectes)*

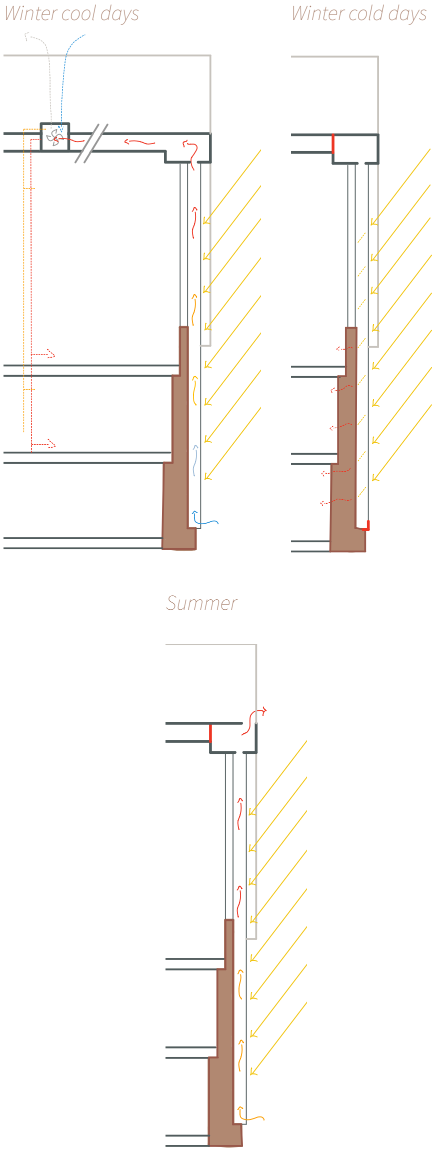


Figure 42. Solar wall system (Adapted from Nunc, Alsace Architectes, Personal communication)

PROPERTIES EVALUATION - SOLAR WALL RAMMED EARTH

Information gathered during an interview with Mr Louis Piccon, from Nunc Architectes

Aesthetics - Strong architectural expression that reflects the local constructive traditions (massive walls) and creates a dialogue with the purpose of the building. In addition, it is a raw material that can both be the core and the skin of a building. It reflects the work of man with a strong texture and an invitation to touch.

Ecological - The earth comes from a quarry 3km away that extracts gravel and dumps earth. Its use is therefore part of a circular and virtuous approach. However, the earth is load-bearing in the project and a small proportion of cement was added for the stabilization of the walls to meet French building standards.

Comfort - The rammed earth with the solar wall maintains a very stable temperature and humidity level around the year : it blurs picks of heat or cold. The material also provides a muffled acoustics without resonance. Finally, the texture of the material is also very pleasant and is part of the comfort.

Structural - Since rammed earth is used as load-bearing, it needs important amounts of raw materials and the addition of cement. It is difficult today to use earth as a load-bearing solution because of the lack of standards. It is important that the project follows the materials and not the other way around to make it relevant.

Economic - There is little know-how and low automation which makes it expensive. In addition, the double-skin (with insulation in between, necessary to meet energetic standards) increased the need for labor. However, the aesthetics aspect of the raw material makes it possible to do without finishing materials and to save costs.

ENHANCED COMFORT QUALITY*

●●●● *Thermal mass*
●●●● *Temperature stability*
●●○○ *Moisture regulation*
●●○○ *Acoustic insulation*
●●●○ *Room acoustic*
●●●● *Passive heating*
●○○○ *Actinic*

**Subjective analysis based on literature of the project, interview and on the theoretical part.*

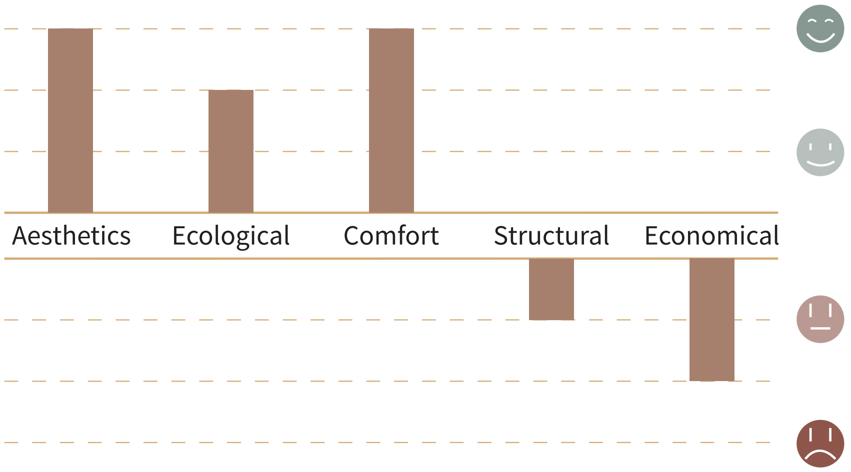


Figure 43. Solar wall and rammed earth Evaluation (By the author*)

RICOLA HERB CENTER

PROJECT ID

Location : Laufen (CH)
Architect : Herzog & De Meuron
Completion year : 2014
Function : Warehouse
Earth techniques :
Pre-fabricated Rammed earth, non-load-bearing
Earthen work : Lehm Ton Erde GmbH

Image 16. *The Ricola warehouse, general view, Herzog & de Meuron (© Markus Bühler)*

EARTH FUNCTIONS

☐	▨	▨	☐
Load-bearing	Filling	Covering	Other

This building is a warehouse for storing and preparing fresh herbs mixtures. The facade is made of pre-fabricated rammed earth elements, each one is 45x425x135cm and weights 4 tons. This rammed earth skin is self-supporting but an inside concrete structure provides the load-bearing function. The elements are manufactured in a factory close to the site and the earth is excavated within a radius perimeter of 8km. However, a trass mortar is integrated every 8 layers to protect the facade against erosion (Herzog & de Meuron, 2014). There have been several iterations for the materiality (Heringer A., Howe L.-B, et all, 2019), and earth was the most suitable for the building purpose, for it's thermal and hygroscopic properties.

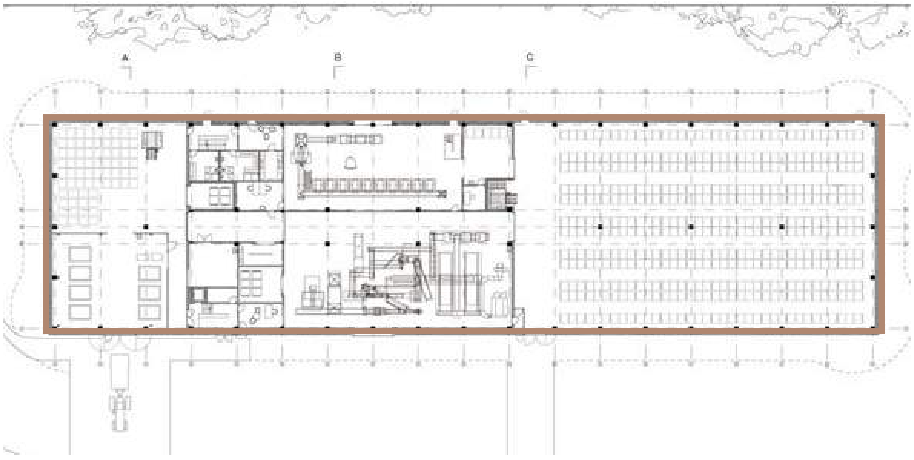


Figure 44. *Ricola Herb Center , plan (Adapted from Arquitectura Viva, n.d)*

__Image 17.__ The Ricola warehouse, Construction (© Markus Bühler)

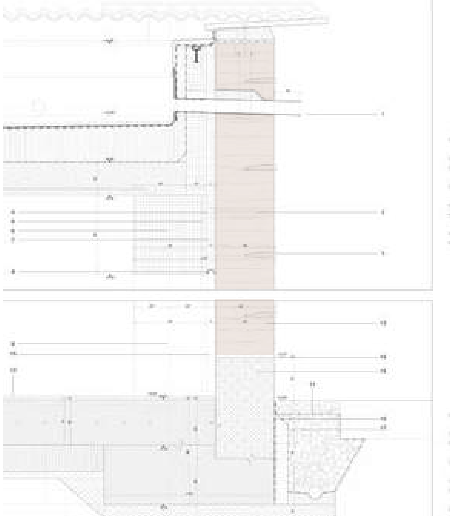


__Figure 45.__ Detailed section (Adapted from Arquitectura Viva, n.d)

PROPERTIES EVALUATION
-
PRE-FABRICATED RAMMED EARTH

Aesthetics - The material and the long monolithic facade adapt to the semi-rural/farming and semi-industrial landscape.

Ecological - Thanks to its natural properties, the earth reduces energy requirements for climate regulations (Herzog & de Meuron, 2014). In addition, the blocks are made with earth extracted within a perimeter of 8km, reducing the transportation emissions.

Comfort - The choice of earth improves the hygroscopic and thermal comfort of the building, which is very important for such use. The thermal mass maintains a very stable internal temperature and excessive moisture (undesirable for the preservation of herbs) is absorbed by the material. Earth was not the first material choice, wood was discussed, but earth was found to be more hygienic (Heringer A., Howe L.-B et all. ,2019).

Structural - The facade is self-supporting but not load-bearing. This function is performed by concrete, however it uses as little material as possible thanks to a punctual structure. Without this solution, the building would not have been accepted by Swiss standards, so the compromise is better than a building made entirely of concrete or steel (Heringer A., Howe L.-B et all. ,2019).

Economic - The prefabrication was carried out in a nearby factory. Thanks to the machines developed by Lehm Tom Erde, the process is mechanized and therefore of better quality and less expensive. The price was a criteria for the choice of the material and the limestone bricks were refused because they were too expensive (Heringer A., Howe L.-B et all. ,2019), which implies that earth was acceptable in terms of price.

ENHANCED COMFORT QUALITY*

●●●● *Thermal mass*
●●●● *Temperature stability*
●●●● *Moisture regulation*
●●○○ *Acoustic insulation*
●●○○ *Room acoustic*
○○○○ *Passive heating*
●●○○ *Actinic*

**Subjective analysis based on literature of the project and on the theoretical part.*

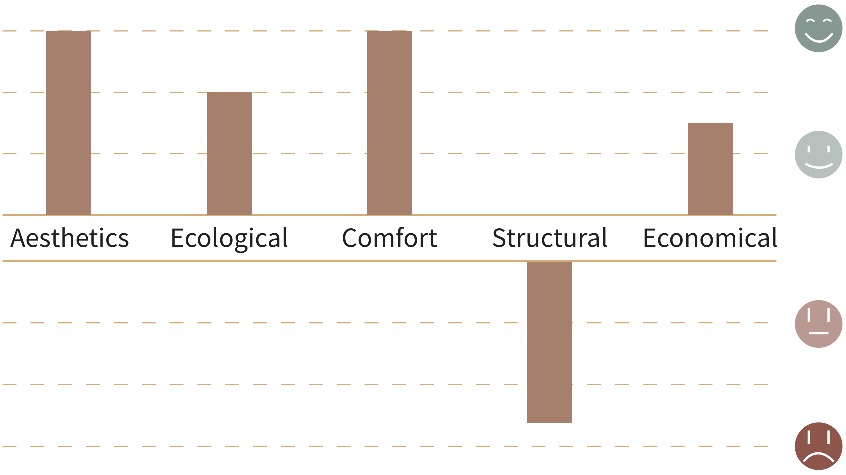


__Figure 46.__ Pre-fabricated rammed earth evaluation (By the author)*

VORARLBERG MUSEUM

PROJECT ID

Location : Bregens (AT)
Architect :
Cukrowicz Nachbaur Architekten
Completion year : 2013
Function : Museum
Earth techniques :
Clay plaster
Earthen work :
???

Image 18. *Vorarlberg Museum, Atrium (©Adolf Bereuter)*

EARTH FUNCTIONS

☐	☐	■	☐
Load-bearing	Filling	Covering	Other

This project is the renovation and extension of the Vorarlberg Museum, whose original building is listed. The conservation of the art works needs a very stable relative humidity, with an allowed fluctuation of up to ±3%, such a museum usually needs high-tech building installations to control it (Dachverband Lehm e.V. n.d). To keep the moisture at the correct level while reducing the energy needs, clay was used to cover load-bearing concrete walls. Also, the suspending ceiling panels are made of earth materials and also covered by clay plaster. In total, clay was applied on more than 150 000m^2 in the museum (Dachverband Lehm e.V. n.d).

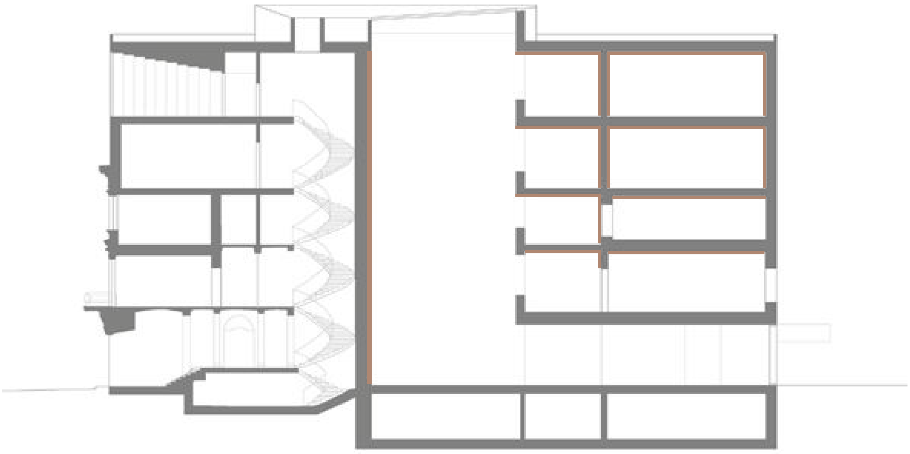


Figure 47. *Section (Cukrowicz Nachbaur Architekten)*

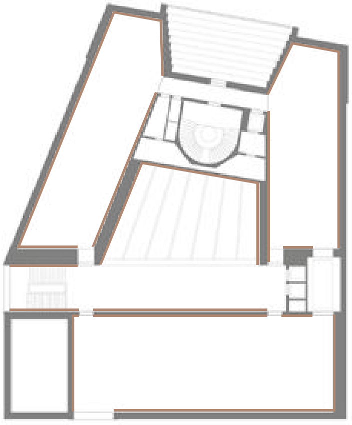


Figure 48. 5th floor plan (Cukrowicz Nachbaur Architekten)

PROPERTIES EVALUATION
-
CLAY PLASTER

Aesthetics - The clay plaster gives the walls of the museum a very pure and noble aspect. The color of the plaster was specially developed for this building. Also in this case, the light passing through the windows makes the tones slightly change.

Ecological - Thanks to natural moisture regulation provided by clay, the need for ventilation and air conditioning is greatly reduced. A study over several years of use has been carried out and the energy required is reduced by 40% compared to a conventional museum (Dachverband Lehm e.V. n.d).

Comfort - The clay plaster mainly affects the hygrometric properties of a room and reduces the need for mechanical regulation. The thick clay plaster (3cm) helps to regulate the humidity of a room thanks to a quick moisture absorption capacity, avoiding peaks of moisture in the building (Dachverband Lehm e.V. n.d).

Structural - The clay is not structural

Economic - Economically, for the same reason as the ecological one, the reduced need for installations has saved a third of the cost compared to a more conventional installation (Dachverband Lehm e.V. n.d). In addition, clay plaster is less expensive than other clay materials because it is less time consuming to implement.

ENHANCED COMFORT QUALITY*

○○○○ *Thermal mass*
●○○○ *Temperature stability*
●●●● *Moisture regulation*
●●○○ *Acoustic insulation*
●●●○ *Room acoustic*
○○○○ *Passive heating*
○○○○ *Actinic*

**Subjective analysis based on literature of the project and on the theoretical part.*

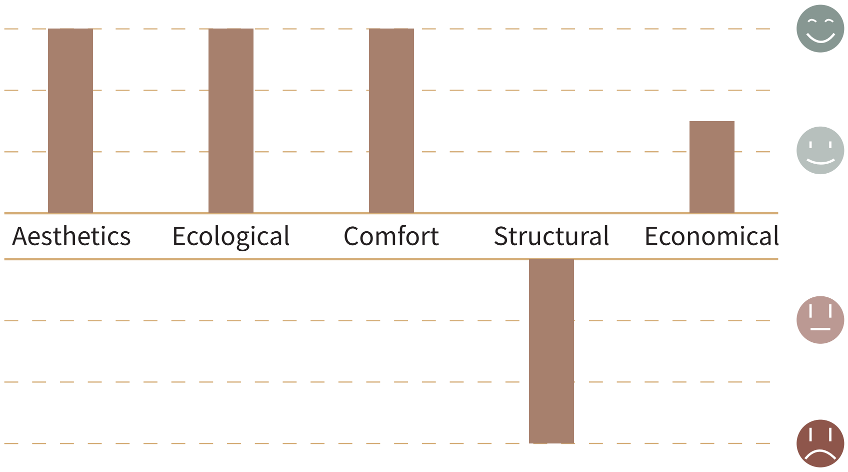


Figure 49. Plaster evaluation (By the author*)

RAUCH HOUSE

Image 19. Rauch house (©Beat Bülher, 2011)

PROJECT ID

Location : Schlins (AT)
Architect :
Roger Boltshauser &
Martin Rauch
Completion year : 2008
Function : Housing
Earth techniques :
Compressed Earth Bricks
Earthen work :
Martin Rauch

EARTH FUNCTIONS

■	■	■	☐
Load-bearing	Filling	Covering	Other

HOUSE MATERIALITY

The house identifies a large number of clay products which are all summarized in the table beside. The material treatment is adapted on the level of intimacy of a room : it becomes more refined as the room becomes more private and vice versa. The garage and cellar are very rough, the layers of rammed earth and hollow clay give a very brutal experience of those spaces, even more enhanced in the cellar by the rocky hill facing the windows. On the other hand, the waxed rammed earth in the bed room mixed with the wooden frame gives a more refined and subtle inside perception (Boltshauser, R., Kamm, T., et al, 2011). Great importance is given to tactile senses and the texture.

Martin Rauch's vision was to create not only a house but a study object. He pursues a radical sustainable commitment and his utopia is that a building can return to nature without any waste or contamination and minimizing its energy use (both embedded and operative). The goal here was set more on the sustainability of the materials than on the operating energy. Studies shows that it has important benefits on the indoor climate.

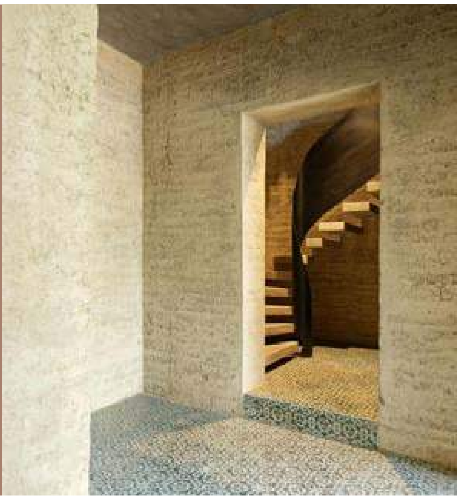


Image 20. The entrance (©Beat Bülher, 2011)

FLOOR	MATERIAL	FUNCTION
Ground floor	Rammed earth	Load bearing walls, inside, straicase and towards the outside
	⬭ Trass-clay	Garage and cellar floor, stairs
	⬭ Hollow clay block	Garage and cellar ceiling
	⬭ Octogonal clay tiles	Entrance, guest room and stairwell floor
	Flat stucco	Entrance, guest room ceiling
1st and 2nd floor	Waxed rammed earth	Floors
	white clay plaster	Walls and ceilings
	⬭ Black fired clay	Kitchen bassin and surfaces
	⬭ Glazed tiles	Bathroom
	Clay casein spackling	woodwork cover
Outside	Rammed earth	outside facade and load bearing
	⬭ Mud bricks	Roof and terrasse cover

⬭ Materials that need to be baked (max 900°C)

Figure 50. *Clay based materials (Data from Boltshauser, R., Kamm, et al. (2011))*

RAUCH HOUSE MATERIALS EVALUATION

Aesthetics - Earth aesthetics are well explored on this project and the material is adapted to the use of room. However, risks were taken to fit a modern aesthetic with a material with high constraint : for example the flat roof without eaves is a risk for such a material which erodes under water.

Ecological - This is an example of resource management, 85% of raw building materials are extracted from the site. The embedded energy of the house is 40% less high than a conventional house ($2300 MJ/m^2 < 4400 MJ/m^2$). Most of the embedded energy is only due to building services installations and the machinery used during the construction that used fossil fuels. (Boltshauser, R., Kamm, T., al. 2011).

Comfort - The advantages on the indoor climate are described in detail the next page. A study shows that the implementation of clay increases the indoor quality compared to a standard house. Clay is natural, free from harmful substances, has antiseptics and moisture regulation qualities that prevent mold formation. This ensures a good air quality without pollutants or odors with adequate humidity and temperature levels ; In the heart of the house there is no cell reception, linked to the electro-smug protection properties of rammed earth.

Structural - In the rammed earth wall of the facade, clay is used for structural purposes. However, ring beams made of stabilized clay are implemented in the wall to receive the intermediate and the roof slabs (Boltshauser, R., Kamm, T., al. 2011) .

Economical - Only the formwork and ramming process represent around 35% of the total price , building with earth is expensive in high wage countries (Boltshauser, R., Kamm, T., al. 2011).

ENHANCED COMFORT QUALITY*

●●●● *Thermal mass*
●●●● *Temperature stability*
●●●● *Moisture regulation*
●●○○ *Acoustic insulation*
●●●○ *Room acoustic*
●●○○ *Passive heating*
●●○○ *Actinic*

**Subjective analysis based on literature of the project and on the theoretical part.*

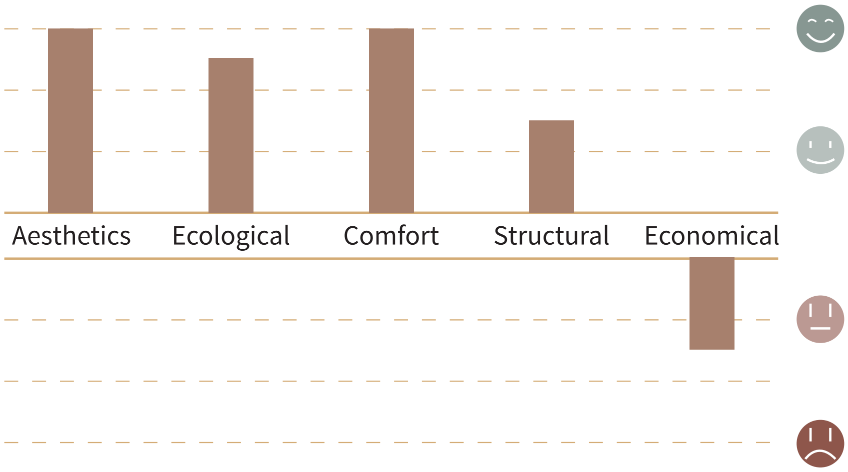


Figure 51. *Rauch House Evaluation (By the author*)*

RAUCH HOUSE

Image 21. *The living room (©A. I. Schnabel, n.d)*

HUMIDITY

The relative humidity of the house is always kept in the comfort zone. A study from the center of Integral Building Technologies ZIG, in Lucerne, shows that in winter, the humidity level is higher and steadier than in a conventional house (Boltshauser, R., et al. 2011). It has a relative humidity almost always remaining above 20%, while it is often below for conventional houses. As the loam can release stored humidity it provides less dry indoor air, which is important for health, as discussed previously. On top of that, the author of the study specifies that the measurements are made without taking into account plants, cooking or showering which have the effect of increasing the humidity in the house. On the other hand, the humidity in humid rooms such as the bathroom never exceeds 60%, thus preventing

TEMPERATURE

The materials maintain a comfortable and constant indoor temperature throughout the year. In summer, the phase shift of the materials and a strategic arrangement of the windows prevent overheating. It was calculated that overheating occurred a maximum of 6% of the time in a year, only in the 2nd floor (Boltshauser, R., et al. 2011). The measurement was made without any awning, so the result could be even better with such an implementation. In winter, the thermal mass of the wall is combined with heating coils. Rammed earth floors can store direct heat gains up to 9 cm deep in the screed then slowly releases it back into the room.

As visible in the figure beside, the temperatures are higher on the first and second floors than in the basement which is half built against and in the hill. The layout of the house has been designed according to the materials and its ability to regulate the temperature.

Image 22. *The cellar (©Beat Bülher, 2011)*

Image 23. *The bathroom (©Beat Bülher, 2011)*

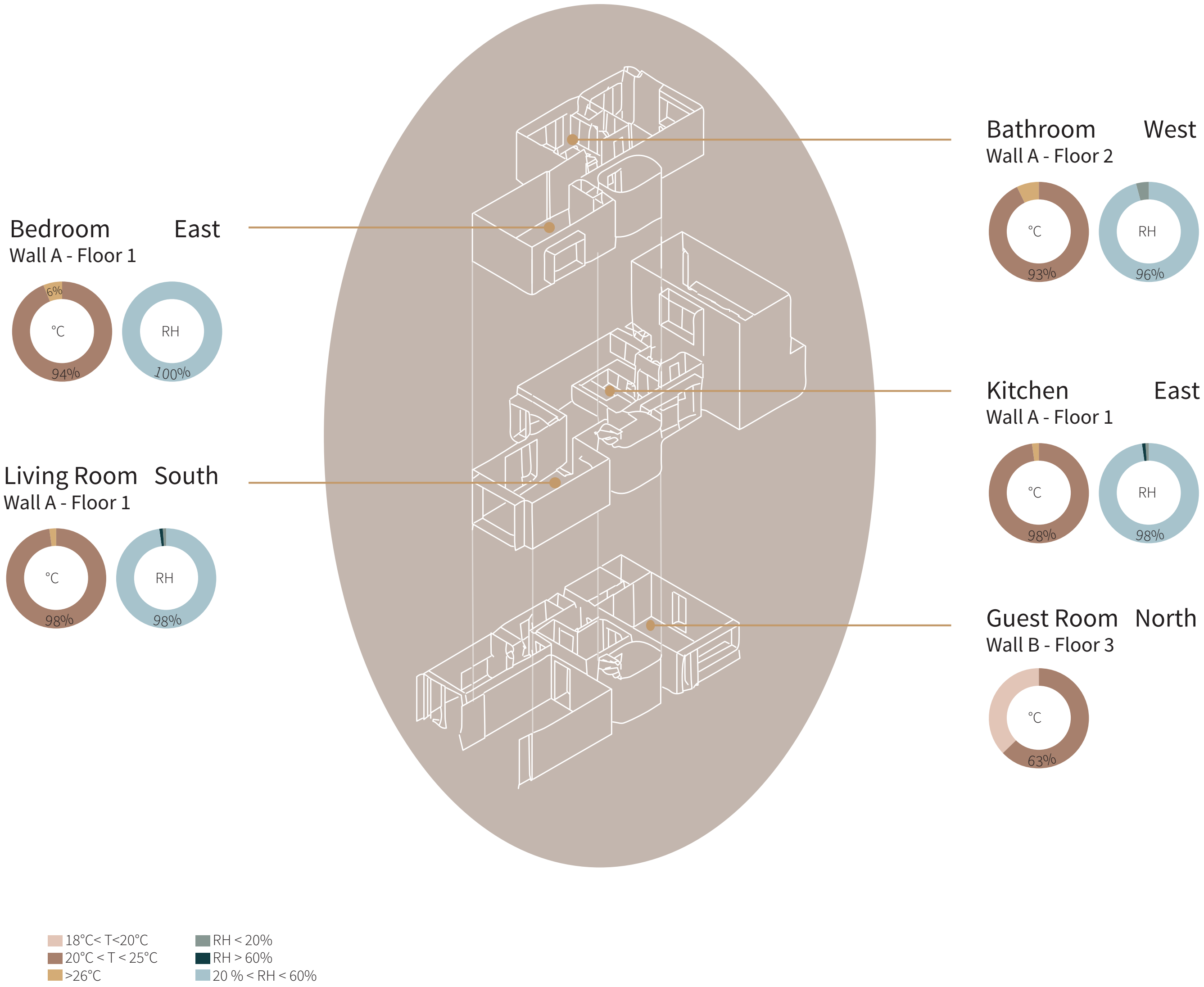


Figure 52. *Rauch House thermal and relative humidity averages on one year operation (Data from : Boltshauser, R. et al. (2011), Axonometry adapted from : Bauhandwerk, 2011)*

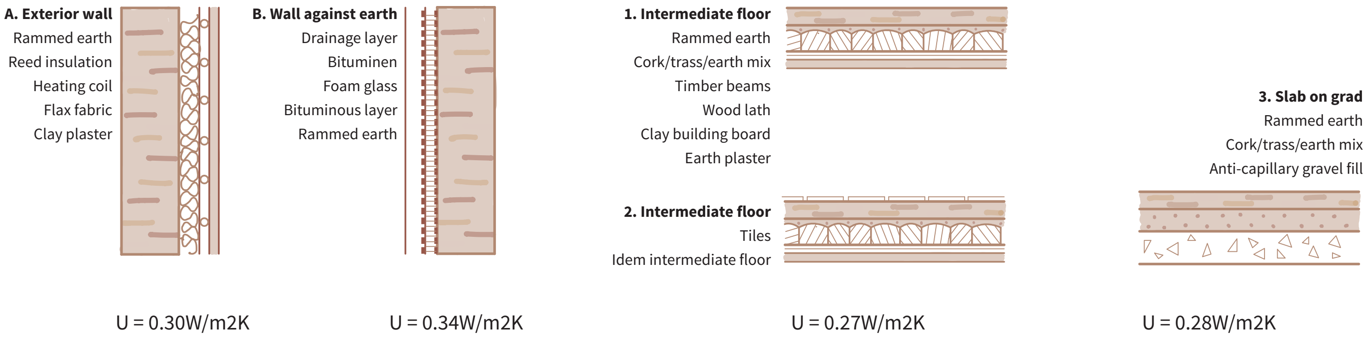


Figure 53. *Rauch house walls and floors type (Adapted drawing from Boltshauser, R. et al. (2011))*

STUDY CASES CONCLUSION

CONCLUSION

The study of these examples highlights the properties and the qualities of earth under different aspects.

First of all, it is noticeable that it is a material which produces a strong architectural expression and which can take many forms. It can be left in its raw form (without finishes) or be the actual finish (clay plaster), it can also be load-bearing or used as a filling for another structural material. Besides, the material is very beautiful, local, and sustainable.

The examples have been selected in connection with the fact that the wish to use clay materials is always linked to a desire to improve the indoor climate, and they highlight its properties in this area. Compressed earth blocks were chosen in the Geisendorf project to provide thermal inertia to a "light" building. In the Vorarlberg museum, clay plaster completes the ventilation system to keep indoor relative humidity constant. Finally, measurement in the Koeppel extension and the Rauch House confirmed its impact on temperature and humidity regulation. On these four buildings, there is no quantitative analysis on its impact on the indoor sound perception of the rooms. However, during the interview with the stakeholders of the Koeppel extension and the Geisendorf project, the sound environment was described as both cozy and felted. These analysis outline that the earth meets indoor climate expectations.

Nevertheless, it is important to point out that there are some drawbacks to use earth as a material as well. Even if they are not directly related to the indoor climate properties, it is important to take them into account when using such materials. The first one is the high cost generated mainly by the lack of automation which implies a high need for experienced workforces combined with high salaries in European countries. It also requires a lot of testing and experimentations (which comes at high cost) to prove the quality of a material that has already proven itself in the past. This is mainly due to a lack of standards, which are currently slowing down the process. To this end, the Ricola Herb Center represents an example of how earth can meet the requirements : prefabrication. This makes it possible to reduce the prices and also to achieve a better material quality. Indeed, the test on the mixture and on the elements can be carried out during the prefabrication in the same way as it would be done for other industrialized materials to check whether the product can meet standard requirements (Heringer A., Howe L.-B et all. ,2019). This could clearly participate in the development of the material's use in the future.

The case studies also present an interesting discussion about the structural properties of earth. It can be load-bearing but that may not be the most appropriate way to use it in buildings. Indeed, there are several drawbacks to use it as a load-bearing structure:

- It requires a large amount of material
- To fit the current building standards, it must be completed with cement which is a nonsense because it reduces the virtuous quality of the materials.
- Finally, it is not possible (nowadays) to build high buildings with earth, even if it has been done in history (City of Shibam) current norms will not allow it to be possible.

Therefore, the use of earth is very relevant as a filling material in addition to other load-bearing materials (such as wood for example). This will improve indoor climate qualities and architectural expression while being rational from the point of view of physical and monetary resources.

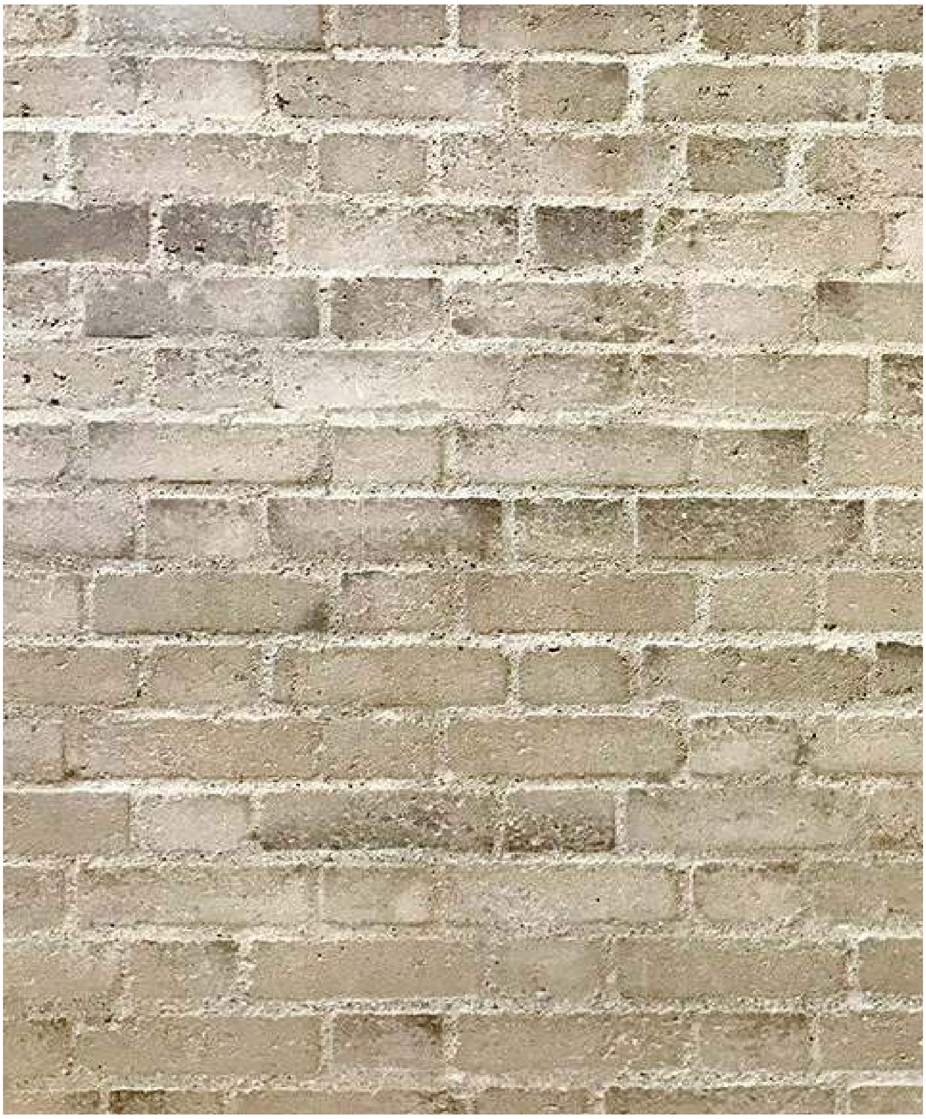


Image 24. *Compressed earth brick wall, Geseindorf (@Terrabloc)*

4

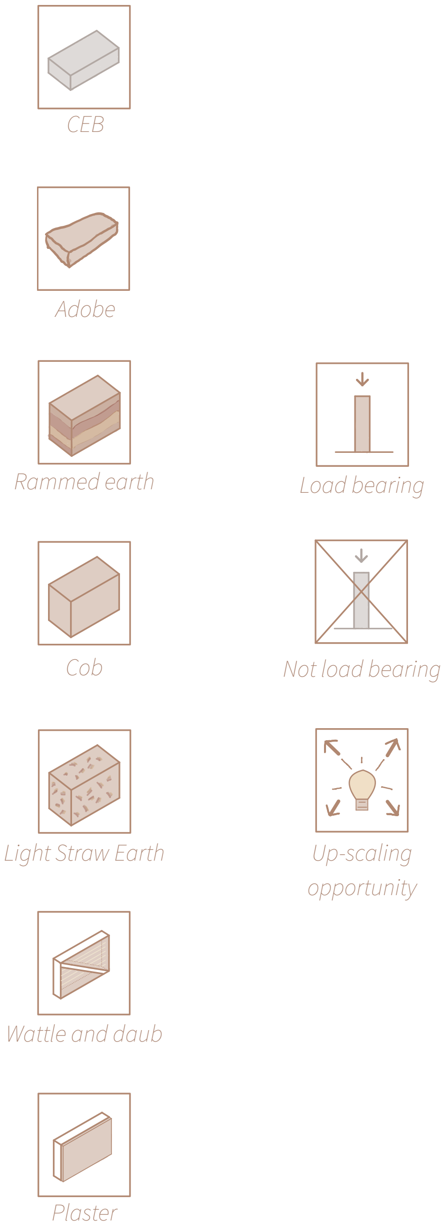
Catalog

This chapter presents different methods that can be used to build with clay to improve the indoor climate. They are classified by element (Horizontal structure, Vertical structure, partition wall, finishes and envelop) and describe the benefits and/or drawbacks.

INTRODUCTION

EARTH IMPLEMENTATION

As already mentioned before, clay is a material that can be used for many purpose in construction. The diagram on the next page was produced by CRAterre, and summarizes the different techniques used to build with earth. Depending on the technique, earth become a load-bearing, a filling or a finishing material. Earth materials can monolithic elements (rammed earth, cob), masonry (compressed earth brick, adobe) or used as a filler of another type of load-bearing structures such as timber (Wattle and daub).
Earth is used in walls, slabs and even in roof elements. However it cannot be used in the foundation due to the high humidity content which could alter the structure through the effect of capillarity. Earth can be used alone or mixed with other elements, such as fibers, the most common being straw: it is used in the implementation of cob or wattle and daub for example, and improves the insulation properties of the material. In this chapter, the aim is to give an example of the variety of implementation and to briefly describe the benefits of each technique. It is a kind of state of the art in order to make the best choice for the testbed. Implementations are classified by element: vertical, horizontal and finishes. In addition two categories are created to show materials that have particular properties in terms of thermal and acoustic comfort. Diagrams are also added to each example, to characterize what type of implementation it is, whether it is load-bearing or not and whether it is a solution that could help upscaling the material. The legend of these diagrams is beside and is used throughout the chapter.



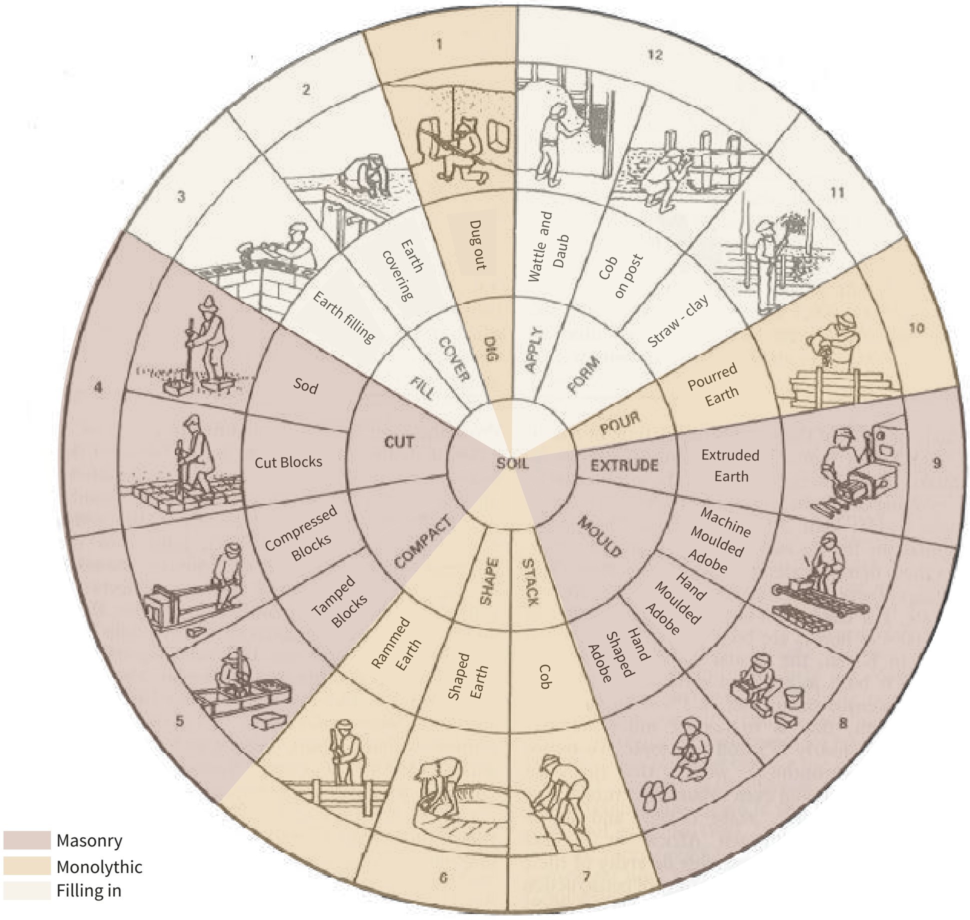


Figure 54. *Wheel of techniques (Adapted from CRATerre, 1994)*

VERTICAL ELEMENTS

RAMMED EARTH

Image 25. *Plazza Pintgia, Switzerland. (Photo : Ralf Feiner, Architect : Gujan + Pally Architekten AG, Location : Switzerland)*

Rammed earth is used for its architectural expression but also for its thermal inertia. The rammed earth chimney can store heat and diffuse it later when it is turned off. Heating coils are also integrated in the load-bearing wall. The main disadvantages of rammed earth are the need for workforce and the thickness of the wall which takes up significant square meters in a project. Because of this, it is an expensive material.

COB

Image 26. *Friend House - Eco Hotel(Photo : Andrew Avdeenko Architect : Ryntovt, Location : Ukraine)*

Molded cob is a clayey earth implemented in a plastic state and can be mixed with straw. In that case it becomes lighter than other monolithic earth uses and therefore brings a better thermal insulation. The fibers also increases cohesion, decrease the shrinkage and increase shear strength. Here clay is both the envelope and finish, also allowing humidity to be regulated. There is a risk of decay if the fibers are not correctly dry before implementation.

COMPRESSED EARTH BLOCS

Image 27. *Pavillon Geisendorf (Photo : Didier Jordan Architect : David Reffo, Location : Switzerland)*

Compressed earth blocks used in combination with a wooden structure are a good mix because they provide thermal mass to the building. Here, the load-bearing function gives an economic drawbacks : tests are needed to proof the resistance, costing money. Finally, it takes time to dry but it can be done in advance in the process and save time on site. It also allows a dry on-site implementation.

ADOBE

Image 28. *Earth Workshop to rescue constructive tradition (Photo : Building trust international, Architect : Building Trust International, Location : Italy)*

Adobe bricks have a lower density than CEB and are made of earth and fibers. It is better for insulation (but generally not sufficient in cold climates). The brick formats allow greater flexibility of implementation and reduce the risk of cracking or shrinkage (compared to monolithic elements). Like cob, the risk of rotting is higher. It is not used that much in cold climates compared to other techniques.

WATTLE AND DAUB

Image 29. *Earth Workshop to rescue constructive tradition (Photo : Building trust international, Architect : Building Trust International, Location : Italy)*

Wattle and daub is a filling and finish technique, it cannot be load-bearing: it needs a support, usually made of wood. This techniques is difficult to industrialize and requires significant craftsmanship knowledge. Generally, it is a lightweight earthen implementation as it is mixed with fibers, which makes it better for insulation and good for hygroscopic properties. It is very open to vapor diffusion which avoids storing water inside.

EXTRUDED EARTH

Image 30. *Residence Eco-Village (Photo : Gernot Minke, Architect : Gernot Minke, Location : Germany)*

It is a method of filling and finishing as well. The implementation is mechanized: a machinery extrudes 2m/min of a wet loam profile, then it is assembled layer by layer. Because of the weight of the upper material on the lower one, only few layers can be done in a day. This system is not load-bearing and needs a higher clay content to avoid cracks in the angle. It is a beautiful and original solution for partition walls which is not well-known but interesting.

PREFABRICATED RAMMED EARTH

Image 31. *Ricola Factory & warehouse (Photo : Iwan Baan Architect : Herzog & DeMeuron, Location : Switzerland)*

We have seen that rammed earth is expensive because of an important need for labor. Therefore, innovative solutions such as pre-fabricated rammed earth can make it cheaper and make optimal use of its advantage. Here the facades are self-supporting but not load-bearing. The humidity regulation offered by the material has a positive impact on the energy use.

3D PRINTING

Image 32. *Tecla project (Photo : Wasp, Architect : Mario Cucinella Architects, Location : Italy)*

Innovative mechanized process that needs important means (large-scale 3D printing), yet since tools is less expensive than manpower it presents material up-scaling perspectives. It is very rational in material use thanks to the hollow structure that can still be load-bearing. It brings the advantages of earth while reducing its disadvantages. Maybe thermal insulation could be added in the hollow structure to increase insulation properties.

HORIZONTAL ELEMENTS

SPALIER DECKS

Image 33. *Loam deck infill (Photo : Walter Unterrainer)*

Earth is poured on thin wooded lathes. When the work is done it is hidden in the slab. Here the earth is quite dense, which will improve thermal mass of the slab and will also be better for the airborne insulation but on the other hand less good for the noise impact. This system can be lightened by straw or other fibers.

PREFABRICATED INFILL ELEMENT

Image 34. *Picture of the element (©Springer International Publishing Switzerland 2016)*

Prefabricated filling solution is in a way a modern version of the Wickel floor. It provides sound and thermal insulation in between floors and also improves the acoustics of the room where it is exposed. Since they are prefabricated, such elements are more rational to be used in modern construction for time consuming reasons. It can also be used for roofing and has the advantage of being a dry building element that does not need drying time.

STRAW LOAM ROLLS (WICKEL FLOOR)

Image 35. *Deck underside (Région Nouvelle-Aquitaine, Inventaire général du patrimoine culturel – Baptiste Quost , 2012)*

Rolls of earth and straw around a wooden batten are fixed in between the beams. It is an old technique mainly used in old barns and in renovation. If left visible as in the example, it improves the acoustics of the room underneath. It is mixed with straw and therefore better for insulation, but the gap between the rolls could make it less efficient. This is a time consuming method, each stick must be rolled one by one.

ROOF INFILL

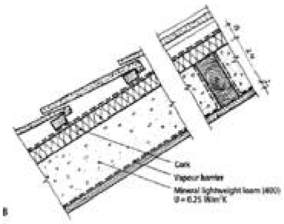


Image 36. *Left Roof infill details (Minke, G. 2009)*

Image 37. *Right Roof infill picture (Luc Floissac, 2005)*

A light earth filling in the roof is used sometimes. The mix must be very light to be thermal effective. The left section shows a lightweight loam of 400kg/m^3 and allows a U-value of 0.25 W/m2.K. It can be completed with a clay panel and clay plaster on the inside. Usually, all the different slabs possibilities can also be used in the roof and this type of infill could also be used in the walls.

FINISHES

RAMMED EARTH FLOOR

Image 38. *Chapel of Reconciliation (Photo : Bruno Klomfar, Architect : R. Reitermann & P. Sassenroth Location : Berlin)*

As a floor finished, a rammed floor is an interesting solution both from the indoor climate perspective and from the aesthetic one. It can be grounded for a terrazzo effect, left raw, or coated with casein or wax to be stronger and easier to clean. (Boltshauser, R. et all, 2011). It is good for thermal mass and especially for the storage of direct heat gains from the sun.

COMPRESSED EARTH BLOCS

Image 39. *Château de Compesières (©Terrabloc, Architects : Ar-ter architecte, Location : Geneva)*

Compressed earth block is also good for flooring. It is resistant and gives a raw appearance. Same as a rammed earth wall it provides thermal mass. In addition it is good for sound insulation. Finally it is a dry implementation, which can be an important advantage and save time in the process.

PANNELS

Image 40. *Apartment renovation (Photo : Lehmag AG, Architecte : Selektiv Studio GmbH , Zurich , 2019)*

Clay panels can be used in many situations both in vertical or horizontal use. It is often covered with a plaster to be more visually pleasing. It can replace gypsum in the partition wall. Generally, the light mixture increases the thermal and sound insulation and also regulates the humidity.

PLASTER

Image 41. *Omicron Relaxing place (Photo : Stefano Mori, Architects: A. Heringer and M. Rauch, Austria)*

Plaster as a finishing surface can be implemented in different ways with smooth or rough surface or various colors and shapes. Textured like in this example, plasters are especially good for acoustics. It also regulates humidity very well, with only a few centimeters thick. More generally, clay plasters are very good for indoor climate.

THERMAL

HEATED FLOOR

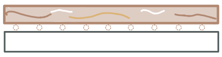


Image 42. *Heating floor illustration (Author)*

A clay screed or CEB floor can be used on top of heating coils to create a heating floor and use thermal inertia. It has a large emission surface and allows the use of a low temperature system. No example is shown because it is hidden in the floor. The downside of this method is that floors often receive significant direct solar heat gains and the heating coils reduce the ability of the earth screed to store it.

HEATED WALL

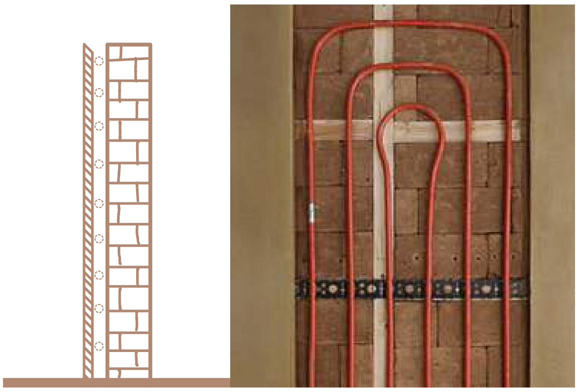


Image 43. *Heating wall illustration (right picture : Ecolut, Architects : Bernhard Bramlage & Mekus Architeckten)*

Instead of being in the floor, the heating coils are integrated into the walls and covered with clay plaster. Placed on a brick wall, it combines its thermal inertia with the high effusivity of clay plaster. It can be used as a heating system in winter and as a cooling in summer to regulate the room temperature. The walls are less exposed to the sun, thus heated walls are more efficient than heated floors according to the previous heated floor description.

GREEN HOUSE

Image 44. *LKH Feldkirch (Photo : Walter Unterrainer) Builder : Lehm Ton Erde Baukunst GmbH, Location : Austria*

Here the thermal regulation properties of the material are highlighted. The wall is not used as a load bearing system but as a cladding. In this south exposed greenhouse corridor, the rammed earth wall is used to store the direct thermal gain from the sun. Curtains can be rolled out in summer to prevent overheating.

SOLAR WALL & PRE-FABRICATED COB

Image 45. *Bâtiment 16 - Campus Beaulieu (Photo : Michel Denancé, Architect : Maurer Architectes, Location : France)*

In this example the glass facade is a thermal skin which eliminates the need for insulation. It showcases the beauty of the material from the outside while being a passive heating system. It takes advantage of the thermal inertia properties of the clay material and the greenhouse effect of glass and has a positive impact on the building's energy use in winter. To avoid summer overheating it must be well designed, with shading or ventilation.

ACOUSTIC

HOLLOW BRICKS

Image 46. *Jeu d'adobe Workshop (Photo : Amaco, Workshop "jeux d'adobe")*

Wall was proposed in a workshop around the exploration of earthen bricks. The brick has an interesting aesthetic, but above all, its shape probably allows a good sound distribution and could increase the acoustic quality of a room. The holes would capture the sound and the porous texture of the bricks itself would also play a role.

ROUNDED CORNER BRICKS

Image 48. *Kindergarten Bellington, 2020 (Photo : Andy Harris architect : Gernot Minke, Location : UK)*

In this project, Gernot Minke uses the rounded corner bricks that he has developed and implemented in several projects. The shape of the brick allows a good distribution of the sound in a dome room in particular. The pattern and the cut-off junction also improve the sound absorption (Minke, G., 2009)

BRICKS PATTERN

Image 47. *Pole Culturel (Photo : Amaco, in "film du lierre" architect : Atelier Philippe Madec, Location : France)*

These compressed earth blocks located in an auditorium are normal CEBs. The specificity of this project lies in the arrangement of the bricks. In this way, it creates a sound trap and controls the reflections of sound on the wall. Thus it creates a good indoor acoustics. CEBs are very dense, therefore they are also good for sound insulation to neighboring rooms.

DIVIDED PANNELS

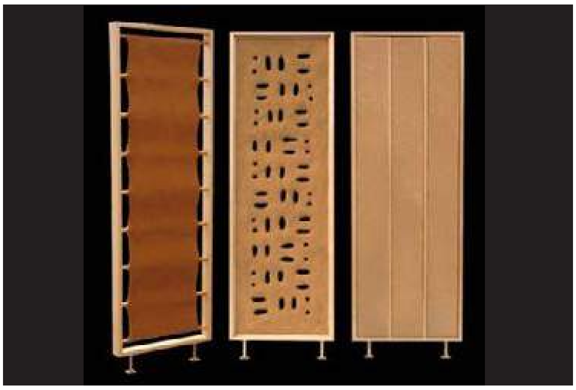


Image 49. *Clay screen divider (Photo : Daniel Duchert, lehm. design.raum, Deutschland)*

These panels can divide the space or be placed in front of a wall, one could even envision it as ceiling panels. Almost like a curtain or a piece of furniture, it will influence the acoustics of the room. Thanks to the wavy shape, the left panel would not only absorb but also redistribute the reflected sound. The middle panel would trap the sound in the hole and decrease reflection. However, these panels are fragile.

5

Generic design

This chapter aims to illustrate and present in a current project how techniques of the previous catalog can be applied in an optimal way. First, the context of the Hoppet project is briefly presented as well as the quick analysis of the rooms in relation to the indoor climate. The presented demonstration axonometry is an example and can be applied to a wider application than that of a school.

INVENTORY & NEED ANALYSIS

> *For children, earth is a natural and challenging material. They can use it for building, modeling, painting, [...], compressing and feeling. All the senses come into play...*
>
> \- Daniel Duchert -
> German indoor Architect and specialist in design with clay and educational rooms

PROCEDURE

The generic design is applied to the Hoppet project that is used as a virtual testbed. It aims to test how clay materials can be implemented. In order to make this generic design development as relevant and interesting as possible, rooms of the Hoppet project were analyzed from an indoor climate perspective. It helped to understand the needs and make decisions for the material implementations. A summary of the needs for the most important rooms of the project can be found beside. The units, the staff room and the common workshop and multy-activity room are identified as the most important, and the response will focus on these areas. The testbed is presented in the next page. The materials from the previous catalogue are selected and suggested for different elements in the Hoppet project. Then, some details are presented for the main section of the east wing of the building as well as an analysis of the behavior of clay for the indoor climate. Finally, a quick LCA study is carried out to compare the new proposition in terms of $C0_2$ eq-emissions.

This part provides an illustrated answer to the main thesis question. It is important to emphasize that the hoppet project serves as a testbed for material implementation, and that this reflection and similar solutions can be used in other contexts other than a preschool.

Figure 55. *Hoppet plans, Ground and first floor (Architect : LINK arkitektur, Constructor : WSP, Personal communication)*

	THERMAL COMFORT	ACOUSTIC COMFORT	ATMOSPHERIC COMFORT	ACTINIC/MECANIC COMFORT
CLASS AND NAP ROOM	Need a constant well distributed operative temperature. Sitting with an «active level» of activity for classrooms. «Low level» of activity for nap room. Significant heat control is needed, and the temperature of the floor is important. Amount of people fluctuates during the day and is often high. A regulation is needed to absorb or release excessive humidity.	Need good sound absorption as well as low and controled reverbation times to avoid echos, making speech audible from everywhere in the classroom. Cozy atmosphere for the naproom. Needs to be well sound insulated from other rooms (common rooms, technical area, toilets...) to avoid noise disturbances during learning.	Children and staff spend most of their day in these rooms : must be free of toxic emissions and chemical materials. Favoring natural materials especially for accessible surfaces. Must provide high air quality. Importance of reducing odors associated with a large number of people in a closed room.	The reduction of electric and magnetic fields in this area can be an interesting point to protect children from this electrosmug. Favor light colors to reflect the light.
ATELJE AND MULTIACTIVITY	Need a constant well distributed operative temperature. «Active level» of activity, not too much heat needed. Center of the building, potential for indirect thermal mass. Amount of people fluctuates during the day and is often high. A regulation is needed to absorb or release excessive humidity.	It can be a noisy area, the acoustics of the room should be controlled to avoid echo and make speech audible (controlled reflection and absorption). I must be properly soundproofed in order to avoid any disturbance in neighboring rooms as it is in the middle of the building and right next to the main classrooms.	must be free of toxic emissions and chemical materials. Favoring natural materials especially for accessible surfaces. Needs for a high air quality, odorless, especially in the workshop, where it might smell like wood or glue. Obviously requires a ventilation system but can be completed with passive strategies.	Reducing electric and magnetic fields in this area is not the most important, it is a meeting place which may require cellular reception. Surfaces must be resistant because shocks can occure. It must be easily cleanable.
STAFF ROOM	Need a constant well distributed operative temperature. Siting activity and «active level» of activity. Significant heat control is needed. Amount of people fluctuates in the day. Small cooking could occure in the kitchenette. A regulation is needed to absorb or release excessive humidity.	In offices and meeting-rooms, it is important to avoid echo, but in a small room it is not that challenging. The break room can be noisy, but their is no critical room around , however avoiding echo could be good.	Need to be free from toxic emissions and chemical materials. Staff spends quite a lot of time here, and it is a place to take break or work, the air quality should allow the brain to rest and recover, or to concentrate.	Reducing electric and magnetic fields is not so relevant here, means of comunication might be needed. Favor light colors to reflect the light.
CLOAK ROOM & CIRCULATION	Constant and well distributed operative temperature. The temperature of the floor in «no shoes» area is important. Humidity regulation would be welcome in certain times of the year or even of the day.	Need good sound absorption to avoid echo, possibly noisy environment when the children are going out or in. Sound insulation is important, so as not to disturb neighboring classrooms.	I should be free of toxic emissions, often chemical materials used for the sake of cleanability and it increase particle emissions. Alternative solution with natural materials worth to be looked at.	Resistance to impacts and cleanability of the surfaces Avoid slippery surfaces when wet Differenciation shoes zone and no shoes zone
HUMID ROOM	The temperature is not of high importance because people spend little time there. The toilets alone will not produce lot of humidity but shower in the changing room will and the excess should be managed.	Avoid echoes, toilets are often made of non-porous materials. These are very sound-reflective and can cause undesired echos. Phonic insulation is required when bathrooms are adjacent to critical rooms such as classrooms or nap rooms so as not to disturb the learning with noise.	Bathrooms are often made of plastic and chemical materials for the sake of cleanability and waterproofing, which increases the amount of emissions. Ventilation is important and can be supplemented with passive strategies.	Surfaces must be cleanable and resistant to possible shocks and impacts.

IMPLEME

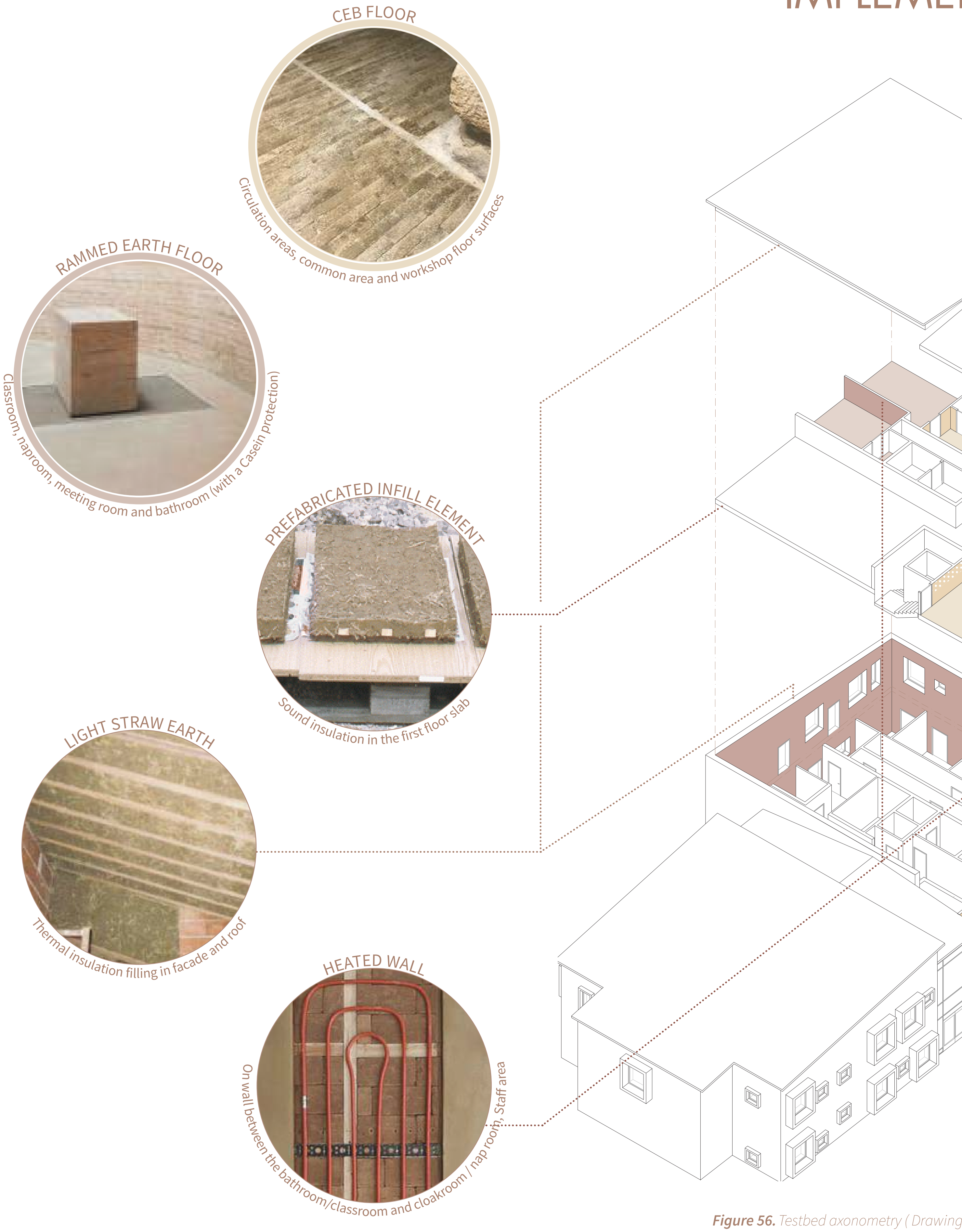
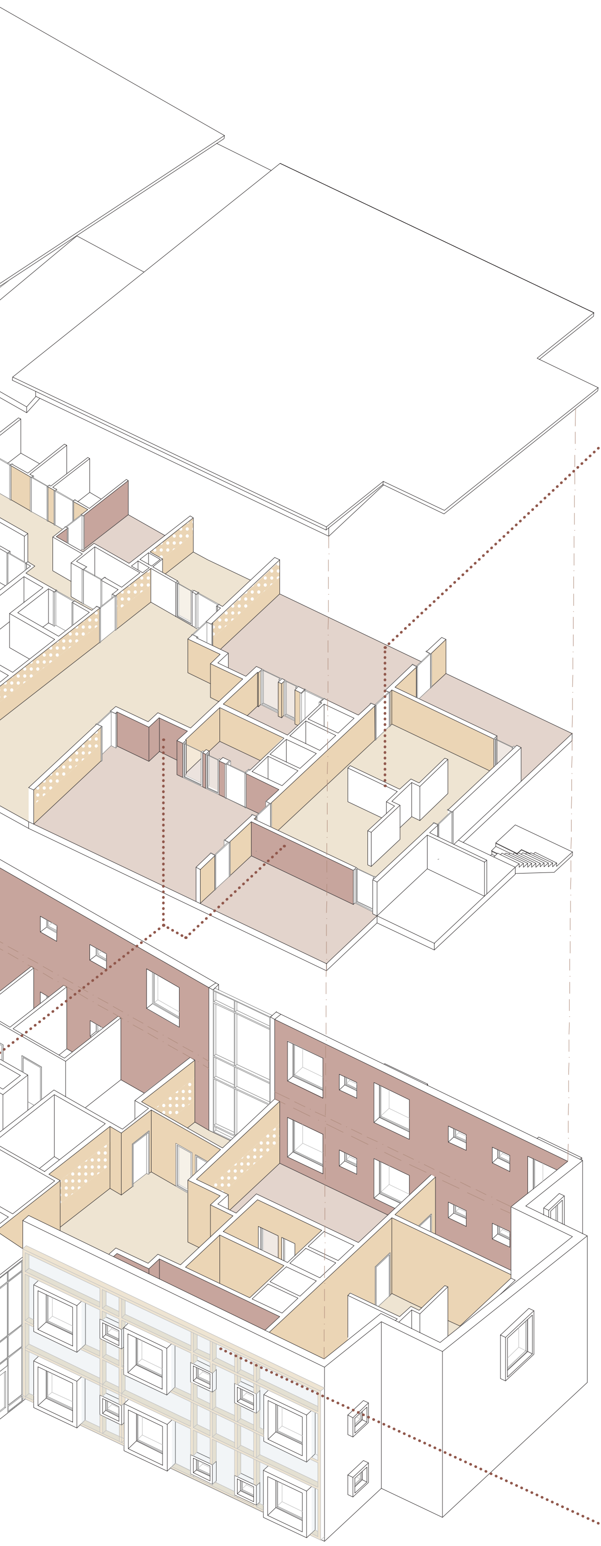


Figure 56. *Testbed axonometry (Drawing*

NTATION



by the author based on the Hoppet plan)

ACOUSTICS CEB

Frieze pattern, Wall of the common area and on one wall of classroom

EXTRUDED EARTH

Partition wall in the cloakroom

CEB WALL

Inner load bearing-walls, visible in some surfaces or combined with plaster

PLASTER

Finish in classroom, naproom and staff

SOLAR WALL

South facade, passiv heating

DETAILS

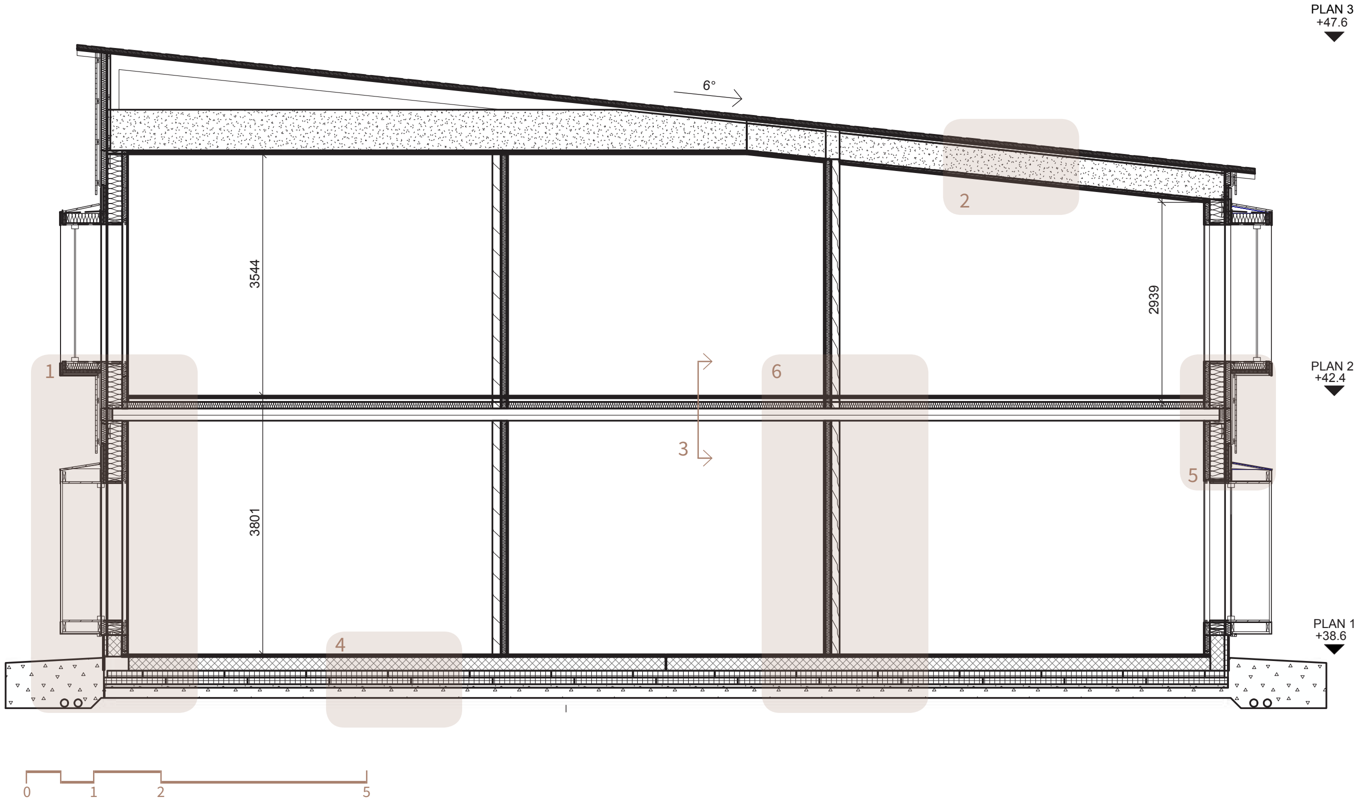
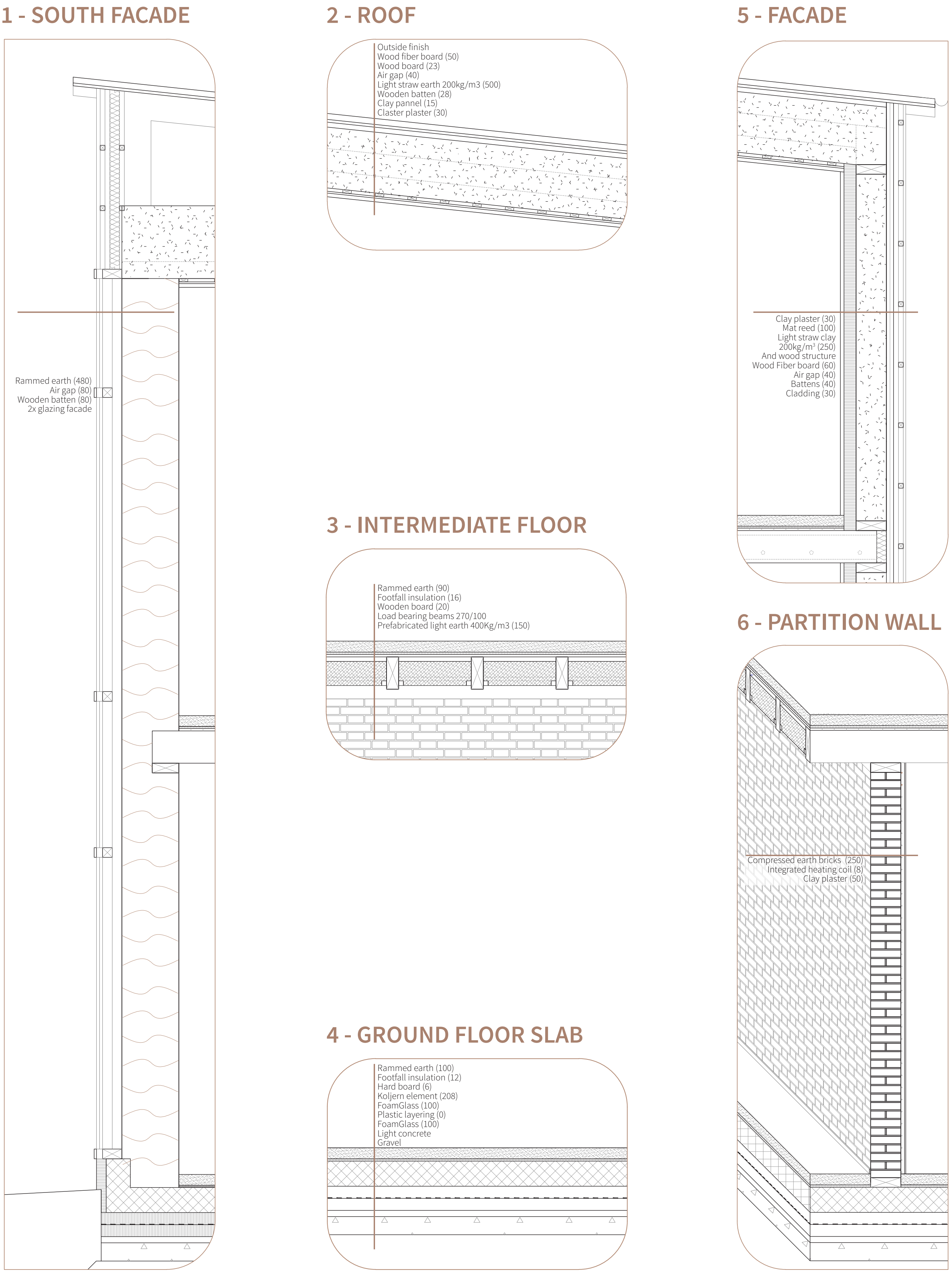


Figure 57. *Hoppet section (Architects : LINK arkitektur , Constructor : WSP, Personal communication)*



1 - SOUTH FACADE

2 - ROOF

3 - INTERMEDIATE FLOOR

4 - GROUND FLOOR SLAB

5 - FACADE

6 - PARTITION WALL

Figure 58. *Testbed details development (by the author)*

ANALYSIS

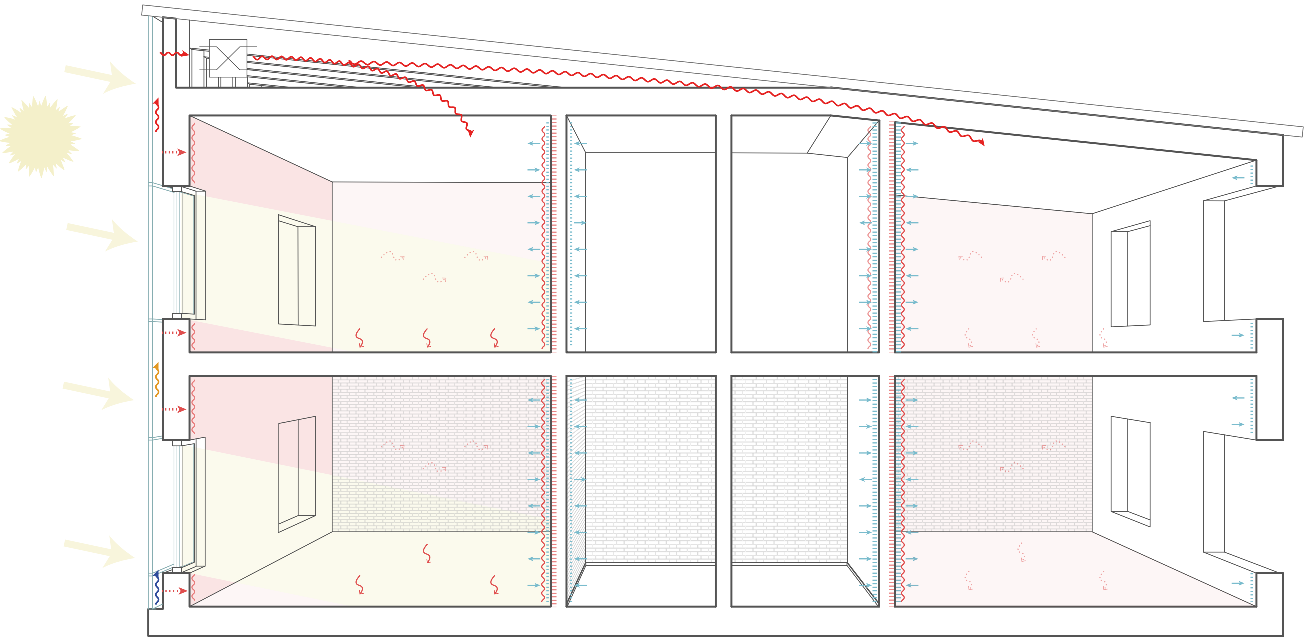


Figure 59. *Action of clay on the indoor climate for the testbed in winter (By the author)*

THERMAL COMFORT

- A solar facade is proposed for the south walls (1). In winter, with a greenhouse effect, the system makes it possible to passively heat the air entering the ventilation. It thus allows the entire building to benefit from this facade and not just the connected rooms. It is also a way to show the material from the outside in a cold climate, the thermal envelop is the glazed facade and therefore no insulation is needed. In summer, an air circulation is created between the glass and the rammed earth to avoid the heating of the air and the storage of the heat and the connection with the ventilation is closed. The thick wall, thanks to the phase shifting, would release the eventual heat accumulation of the day at night when the building is not in use. With a window opening system at night this heat can be easily dissipated. On the other hand, the accumulated freshness will be stored at night in the wall and diffused during the day.
- On the floor, the clay screed implementation increases the thermal mass. When not exposed to direct sunlight (6), it captures indirect heat (produced by appliances, people, and the heating system) while when it is in a position where it can be heated by the sun (7), it captures and stores passive solar heating. It optimizes heat gains and therefore reduces the building's energy consumption and improves the thermal comfort in winter. In summer, with an efficient ventilation system, the coolness of the night would be stored in the floor and diffused slowly during the day to keep a cool climate.
- The walls which divide the bathroom and the classroom (4) are in CEBs visible from the bathroom but covered with a plaster combined with heating coils towards classrooms. The heating system can be supplied with a low water temperature thanks to a high surface emission, combined with the thermal mass of the brick to optimize the system. On top of that, these walls are almost never exposed to direct sunlight and therefore will not reduce the ability to capture direct passive heating. The clay plaster will also improve the humidity regulation in the classroom : it will capture and release excess or lack of humidity faster than wood.
- For the insulation of the roof (2), a very light earth straw mix is used to insulate the building. A clay panel cover with clay plaster finishes the element inside.
- The solution proposed for the facades that are not exposed to the south aims to keep the wooden structure but to replace the insulation

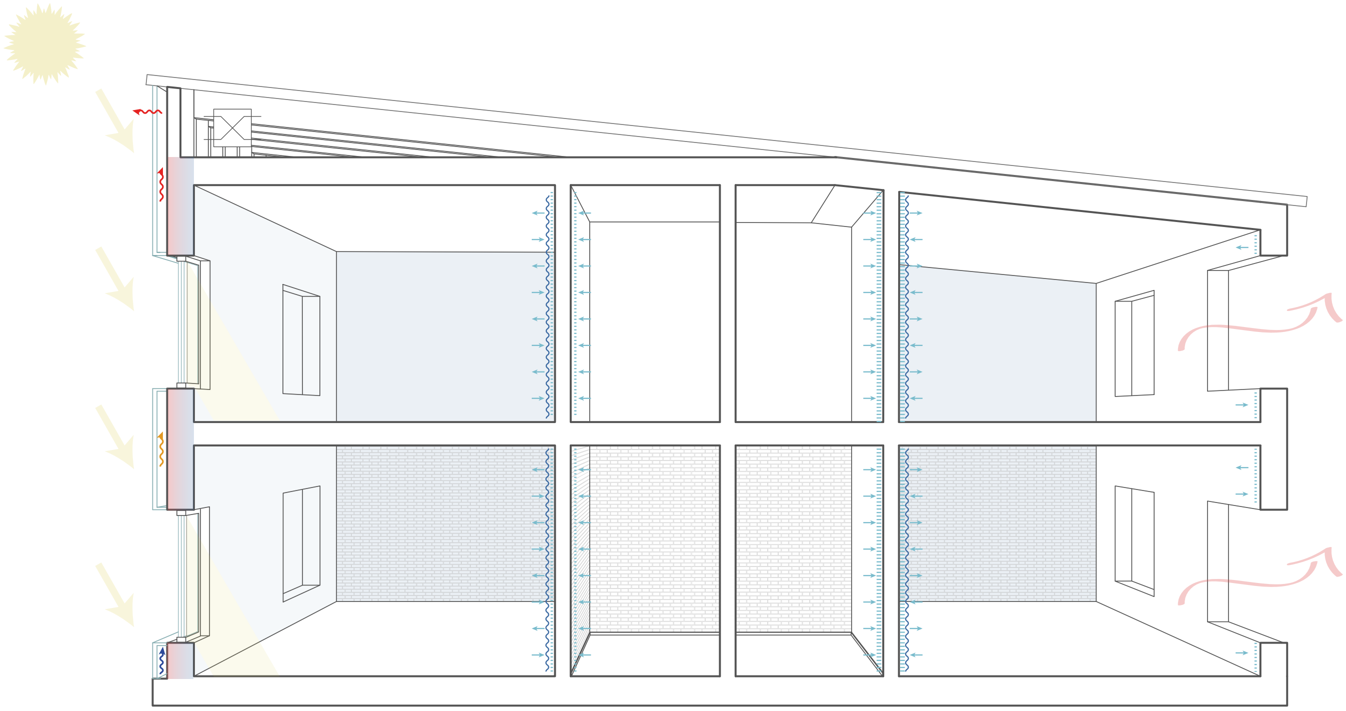


Figure 60. *Action of clay on the indoor climate for the testbed in summer daytime (By the author)*

with a mix of very light earth and straw. The Lambda value of the mix is lower than the one of a conventional insulation, the U-value of the wall is a little lower. Therefore, the solution proposes to keep a layer of wood fiber insulation on the outside, more suitable for earthen construction than the rock-wool layer proposed in the original version. On the inside, the solution uses a layer of reed mat insulation, again more suitable for earth construction than the original material, it will provide a good support for the clay plaster.

ACOUSTIC

•The wall that separates the multi-activity room and the classrooms is made of compressed earth blocks (5) which are kept visible from both sides and implemented with specific patterns. With these patterns, the acoustic of the rooms is improve. The brick wall is also good for sound insulation of the classroom from the noise of the multi-activity room and vice versa.

•The intermediate slab, made of prefabricated earthen elements underneath allows a good sound insulation between the two separated floors and creates a good acoustic qualities inside the room.

ATMOSPHERIC AND ACTINIC

• The massive rammed earth of the south facade, and the CEB walls will reduce the amount of electromagnetic fields entering the building.

• Plaster and rammed earth will also capture odors, emit no emissions and absorb pollutants from the air.

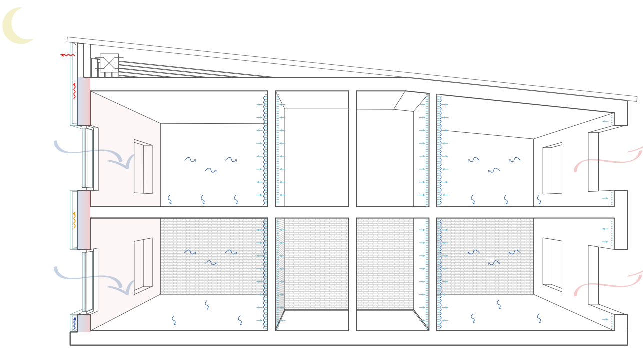


Figure 61. *Action of clay on the indoor climate for the testbed in summer nighttime (By the author)*

COMPARISON

INTRODUCTION

The table beside summarizes and compares the emissions of the original Hoppet building materials and those from the clay material from the testbed. The comparison is made for the six different elements which are presented in detail previously. The calculations were done with the PHPP program, and the detailed calculations are presented in Appendix D. It is important to point out that the values presented here, calculated with PHPP, are not exactly the same as those calculated by Derome (Calderon R., Ryberg A., 2021), stakeholder in the Hoppet project. Nevertheless, the range of values is similar. This difference can be explained by the fact that the different softwares index their calculations on different reference values depending on the material bank. However, in order to compare them in the best possible way, I used in both cases the value that I calculated with the predefined PHPP material list.

CO_2-EQ EMISSION

From a general analysis, we can see that the emissions are slightly lower for the testbed proposal than for the original one, except for the south facade. This is due to the glass which represents a high emission level. On the other hand, the glazing system could use reused glass panels, and in this case the emissions would be lowered. The table also highlights that the two ground floor slabs are similar in terms of emissions. This is due to the fact that clay can not be used in the ground floor slab, due to humidity reasons. Thus, the slab has been kept as the original and only the finishing material changes. Generally, using clay as a finish fits well with the Hoppet ‘s “Exclude and Minimize” strategies as it is both the support and the finish material, reducing the amount of material needs. Finally, transport is not included in the calculation of the emission, so the clay would probably be even more advantageous since it can be at a radial distance of less than 10km, which is not always the case for wooden elements.

CO_2-EQ STORAGE

According to the calculations, the storage capacity of the Hoppet proposal is in average greater than that of the demonstration project. Indeed, the CLT used in the Hoppet project generates a lot of CO_2 storage while it is not the case for clay. There is storage in clay only when the loam is mixed with straw, as it is the case with the facade and the roof in the testbed. On the other hand, clay materials have a lower CO_2 impact during production than CLT. This point underlines, in my opinion, the fact that it is good to consider using both materials in a project : wood for structure and the CO_2 storage, and earth as infill, for the low CO_2 emissions and the good indoor climate it produces.

U-VALUE

U-value for earthen materials is obviously less good, but the thermal mass should help to keep the heating demand low. However, it is important to be aware that a balance must be found between the CO_2 emissions linked to the production of the material (Embedded energy) and those linked to the building’s heat demands (Operational energy). It would be interesting to do a more in-depth study to compare the energy demand of the two solutions with the PHPP program in addition to the simple LCA to have a complete picture, but this was not the scope of this thesis.

CONCLUSION

Even though the difference is little, we can conclude that clay materials generally reduce CO_2 emissions. The values are given for 1sqm of elements only and therefore have a significant impact on the scale of the entire project. In addition, the comparison is made with a project which already aims to reduce emissions as much as possible. This means that there is a huge improvement gap for usual buildings.

Eventhough the storage is lower with earth, it can be reused endlessly, unlike wood which is burnt after its lifetime, releasing CO_2 eq-emissions. Therefore, I think it is more sustainable to reduce emissions as low as possible rather than trying to compensate them, because the day we can produce emission free, we will not need compensation anymore. According to that, clay is more interesting than wood.

Building Element	Cases	Emission kg CO_2 - eq/m^2	Storage kg CO_2 - eq/m^2	U-value W/m²k	Detail Width mm
South Facade	Hoppet	43	81	0.118	506
	Testbed	79	10	/	680
Roof	Hoppet	44	31	0.08	569
	Testbed	22	114	0.16	686
Intermediate Slab	Hoppet	25	148	-	315
	Testbed	22	58	-	326
Ground floor Slab	Hoppet	56	14	0.106	428
	Testbed	55	11	0.105	526
Other Facade	Hoppet	43	81	0.118	506
	Testbed	21	127	0.159	550
Partition Wall	Hoppet	21	108	-	202
	Testbed	13	2	-	300

Figure 62. *Hoppet and Testbed proposal comparison on LCA and U-value (By the author)*

Best value

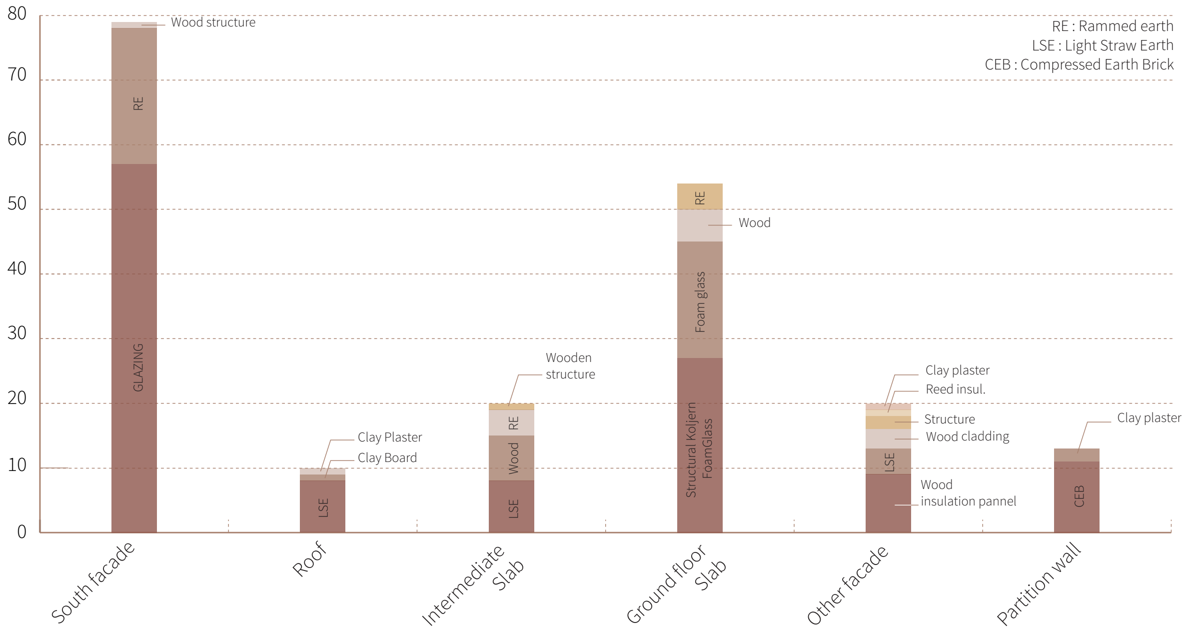


Figure 63. *CO_2 - eq/m2 by element composition in the testbed (By the author)*

FROM GROUND TO BUILDING

RAW MATERIAL

The diagram beside explains the different stages that would be necessary to build with what is under our feet. The first thing to know is if the site's soil is made of earth. In the case of Hoppet, the project site is located on bedrock and very little clay can be found. In this case, it is possible to search for available resources around the site in a small area, usually city-wide. As explained in the theoretical part, the city of Gothenburg undergoes many excavations for the extension of the city and the development of infrastructure, so clay can be easily found within a radius perimeter of about 5 km.

SIMPLE TESTS

When earth is found, it needs to be tested to know if it can be used for construction. The first step consists of carrying out simple tests, as described in the chapter "clay in practice". Such test can be carried out directly on-site without significant means. For larger tests that would require specific conditions or tools, a sample can be sent to a laboratory for further study. If the material begins to be widely used in the city, it is possible to imagine a mobile laboratory, which could move according to the site for example.

EARTH MODIFICATION

After these simple tests, the composition of the earth is known and a decision needs to be taken about how it should be corrected to make the desired earth material in the project. For example, in the testbed, a rammed earth wall is proposed for the south facade. On page 36, we have identified that Marieholmstunneln clay is very fine loam. In order to make rammed earth walls, it is necessary to have bigger aggregates in the mixture. Therefore, if the earth previously tested in this master's thesis were to be used for the testbed, an addition of sand and gravel would be required. A resource mapping step would be necessary. For instance, a quarry exists near Landvettersjon, about 15 km from the Hoppet site, remaining within an acceptable perimeter for local resources. After the identification of earth modification and the resources mapping, the mixing can be done.

PROTOTYPING AND STRESSES TESTS

From there, prototypes can be made to carry out checks on the stresses applied to the element, since the material is not subject to any standard. This prototyping step can be carried out on-site if a small workshop can be set up, or it can be carried out in a nearby workshop or research center with the necessary equipment.

BUILDING STAGE

Earthen materials can be implemented in different ways. They can be directly implemented in the building or they can be pre-fabricated. The prefabrication can be done on-site or off-site. In this second case, a small production plant can be set up near the construction site for the production of materials, as it was done for the Ricola factory in Switzerland, presented in the case study. In this case, the same site could be used for the previous prototyping and tests for example. Prefabrication would probably be the solution used for the Hoppet project since it helps to reduce the cost, as well as to manufacture the material in advance and without the weather constraint. This production line could manufacture the rammed earth facade elements, and the prefabricated infill elements for inner slab, the compressed earth brick for the floors and walls, as well as the extruded earth for the cloakroom. While the clay plaster, and rammed earth floor and light straw earth infill would be implemented directly on the construction without prefabrication.

Figure 64. Resource mapping (By the author)

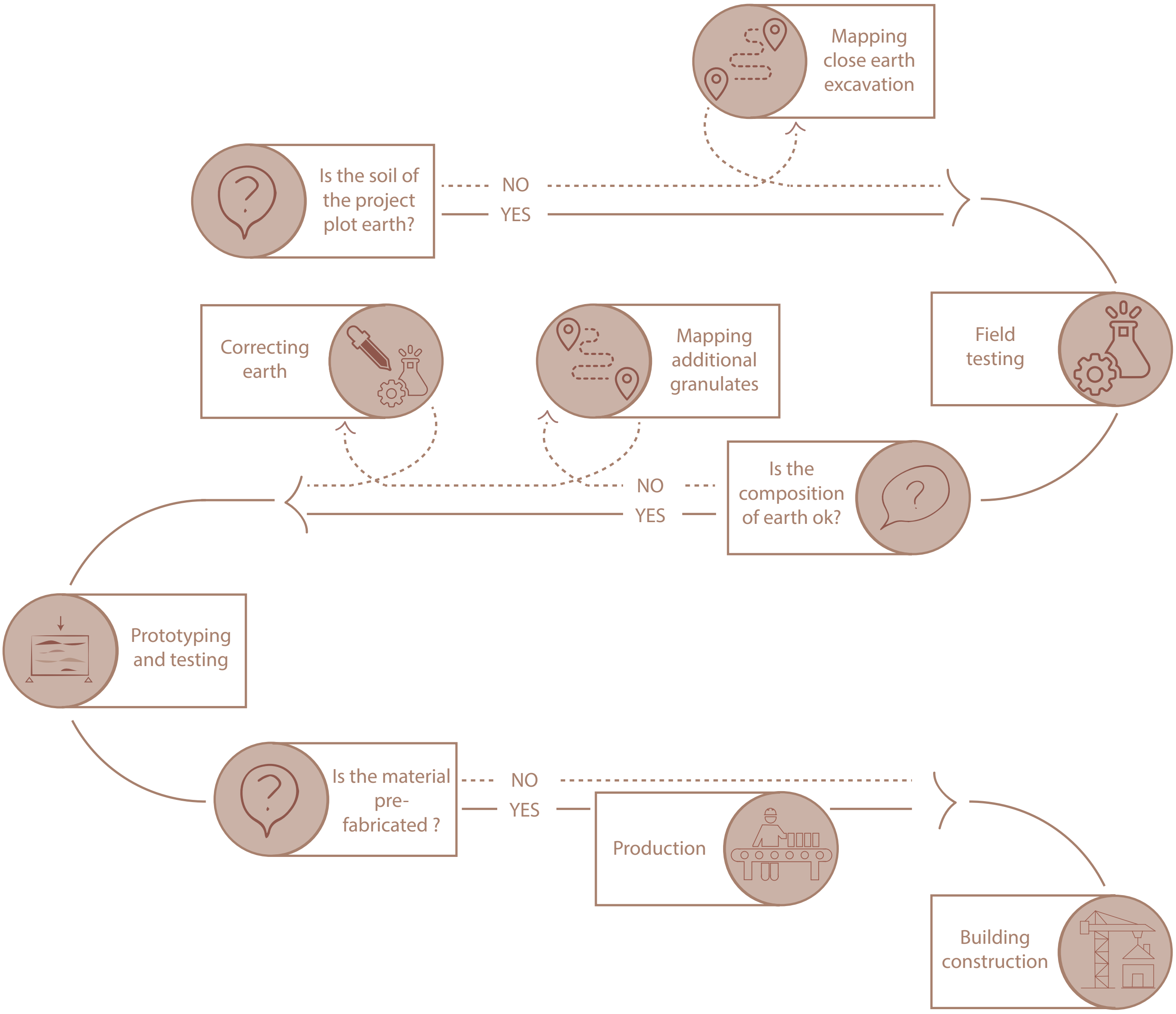


Figure 65. *Process from ground to building (By the author)*

6

Conclusion

REFLECTIONS

RELEVANCE IN THE FIELD

We are looking for new solutions to build with low emissions when part of the answer is right there: under our feet. We are throwing away a material that ticks many boxes when it comes to sustainability.

Here in Göteborg, the Re-circulate project aims to promote the use of materials that already exist in the urban environment and to research on material flows and circularity to decrease the emissions. Excavated clay is one of the materials they examine, as well as the reuse of materials from deconstruction. (City of Gothenburg's official website, n.d). The amount of earth excavated in Göteborg, which was described in the introduction, is not an isolated situation. Across Europe, more earth is being excavated every day to build new infrastructures. Several projects emerge with the same guidelines as that of Re-circulate. The Cycle-terre project in Paris is a great example, as it aims to create different earth materials from the excavated earth from the new underground railway of the Grand-Paris (Cycle-Terre, 2021). A major housing project in the region will be the first construction in which these materials will be implemented.

These examples highlight the relevance of such research, and anchor this Master Thesis in a broader context and discourse. The aim was to emphasis one more reason to use this excavated clay, to promote it and give it more importance. Therefore, it is important to stress that the reflection on this Master Thesis was carried out in the local area of Göteborg, but that the same process could be applied in other cities.

LINK TO THE QUESTION

Earth is well-known for its quality of comfort in warm climate, and most people think that it is not compatible with a cold and humid context, which can be a retarder in projects, due to a lack of awareness. While in fact, it has many properties which are also very beneficial in a Nordic context. This observation is at the roots of my thesis and guided me towards my research question: How to take advantage of excavated clay for the indoor climate benefits of sustainable buildings in a Nordic context?

To answer this question, I conducted a literature study, to understand and explain what are these specific properties we are talking about, and how earth, and in particular clay, interacts with the different environments that define the indoor climate.

Regarding the local context, I also carried out tests to know the material I was talking about. It was important to understand the materiality and if this earth was suitable for construction. It was necessary in order to make the thesis relevant, complete, and anchored in its specific context.

The case studies describe well-known ways of building with earth and evaluate its properties regarding the indoor climate, they also present what is done with earth in Europe. Finally, the catalog chapter presents several existing earth materials. A kind of state of the art to learn more about the possibilities, and to showcase the variety of solutions. It is also a document that shows the beauty of the materials and can increase awareness and provide ideas when planning a building. Later in my work, I used this document to select the earth material for the testbed, based on the need of the different rooms. I hope that this document can be used as a small handbook of different earthen solutions and that it can even be completed in the future.

The heart of the answer lies in the demonstration project. The use of a project such as Hoppet was the ideal testbed for this master thesis since the project promotes sustainable building, fossil-free construction, and low CO_2 emissions. Besides, the Re-circulate project is also carrying out a study to implement earth in the Hoppet preschool, which makes this Master Thesis relevant, and hopefully useful for this purpose. With this testbed, it was possible to show how earth can be integrated into a building, so that it increases its interaction with the indoor environment in the best possible way. In terms of indoor climate, the link between the theory and the testbed highlights the properties of the earth and the benefits that would occur qualitatively. The next step would be to do some lab or in-situ tests to analyze the difference quantitatively, and maybe this is something that could be developed through another Master Thesis. The Master Thesis focused on this testbed, but the concepts applied could be used in other projects. This testbed can be seen as an example to lay on in future projects.

CONCLUSION

In conclusion, it can be said that excavated earth can obviously increase the indoor climate quality of buildings, and the demonstration project illustrates how. Perhaps it also points out that it should be used primarily for this purpose, more than for structural reasons. Although it is the oldest building material, the use of clay represents a greater effort than the use of usual materials because it still lacks standardization. It is today the main retarder of development in the field. Therefore, I would like to highlight once again that it must be used within its structural limits and properties to make its use legitimate and create sustainable and resilient buildings. It would not be rational to try to build high-rise buildings with structural earth, it would consume too much energy and materials. However, as explained previously, the synergy between earth and timber is very good, and maybe a mixed system should be studied and could be a potential opportunity to use earth in larger projects. Each material must be considered and implemented for its advantages, and we must not try to go beyond its properties. We have to use earth in the right place. Such solutions could help to “up-scale” earth, to take advantage of its good indoor climate and environmental properties and to be coherent.

PERSONAL DEVELOPMENT

From a personal point of view, I have enjoyed studying this topic very much. I sometimes got lost in very interesting and fascinating readings, always amazed by what I discovered. At first, I had a fascination for rammed earth, but it was because I didn’t yet know all that earth has to offer. Now that I know more, and that I have discovered other techniques, I am even more impressed by this material and its almost limitless possibilities in terms of design, texture, shape, and amazing properties... And I hope it could do the same for those who read this work.

Now, I want to take all this knowledge with me and use it in my future work, I hope to have the chance to work with clay soon and finally put this thesis into practice and work for sustainability. I am convinced that the field will change and that we will build more and more in a “clay-ver” way.

7

References

GLOSSARY

CIRCULARITY
Economic model which eliminates the term of waste by considering it as a resource to produce more sustainably

CLAY
Define a clayey earth, thick heavy loam that contains an important amount of clay particles. It is soft when wet and hard when it is dry or baked which make it useful in construction

CO_2-EQ EMISSIONS
Measure making possible the comparison of the emissions of several greenhouse gases according to their global warming potential (GWP). Each gas is converted based on the GWP of CO_2

EARTH
Generic word to describe a loam as a raw building material

EMBEDED ENERGY
energy used to create the material in the production stage of the life cycle

GREENHOUSE GAS EMISSION
Gas emission such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and some other, that are related to human activity.

INDOOR CLIMATE
See page 22-23

LIFE CYCLE (ASSESMENT)
It asses the environment impact of a product or a building during all its stage : from cradle to grave or to cradle.

OPERATING ENERGY
energy used by the building during it usage stage, it is the electricity to make the building work : electricity, heating, warm water…

STABILIZED (EARTH)
earth mixed with trass, cement or lime and decrease it circular properties

ACRONYM

CEB
Compressed Earth Block

CO_2
Dioxyde de Carbon

CO_2-EQ
Carbon Dioxyde Equivalent

GWP
Global Warming Potential

RE
Rammed Earth

SGI
Swedish Geotechnical Institute

VOC
Volatic Organic Compounds

WHO
World Health Organisation

REFERENCE LIST

WEB SITE

Amàco. (2020, December 10).
CURVE // Banques d'accueil en pisé. https://amaco.org/curve-mobilier-daccueil-courbe-en-pise-fin/

Arentsen, A. K. (2019).
Living Lab Event became EU Green Week Partner Event! Interreg North see Region. https://northsearegion.eu/northern-connections/news/living-lab-event-became-eu-green-week-partner-event/

City of Gothenburg's official website. (n.d.)
Hoppet - Ett innovationsprogram för fossilfri byggnation - Forskning. Göteborg Stad. Retrieved May 2, 2021, from https://goteborg.se/wps/portal/enhetssida/hoppet-fossilfri-byggnation/forskning?uri=gbglnk%3A20193189395479

Cycle terre. (2021, March 20)
Le projet. https://www.cycle-terre.eu/cycle-terre/le-projet/

Dachverband Lehm e.V. (n.d)
Vorarlberg museum
Retrieved from : https://www.dachverband-lehm.de/bauwerke/vorarlberg-museum-bregenz

Dachverband Lehm e.V. (n.d)
Lehmbau Techniken
Retrieved from : https://www.dachverband-lehm.de/lehmbau/techniken

Herzog & de Meuron (2014)
Ricola Kräuterzentrum. ArchDaily. Accessed 7 May 2021. https://www.herzogdemeuron.com/index/projects/complete-works/351-375/369-ricola-kraeuterzentrum.html

Kant, H (2020, january 7)
Hur ser Göteborg ut 2035? (P. Krantz, interviewer) Lokalguiden
Retrieved from : https://www.lokalguiden.se/magasinet/artikel/hur-ser-göteborg-ut-2035

(NGI) Norwegian Geotechnical Institute. (n.d.).
What is quick clay? https://www.ngi.no/eng/Services/Tecal-expertise/Quick-clay-landslides/What-is-quick-clay

Nordbygg. (n.d.)
The Hope for fossil-free construction. Nordbygg.Se
Retrieved from : https://www.nordbygg.se/latest-news/hoppet?sc_lang=en

McDonough, W. (2017, August 18).
Cradle to Cradle. Retrieved from : https://mcdonough.com/cradle-to-cradle/ [21/04/21]

Reardon, C. (2013)
Thermal mass. Your Home, Australi's Guide to Environmentally Sustainable Homes, Australian Government. Retrieved from : https://www.yourhome.gov.au/passive-design/thermal-mass#:%7E:text=Thermal%20mass%20is%20the%20ability,timber%20have%20low%20thermal%20mass.

Trafikverket. (n.d.).
Västlänken. Retrieved May 3, 2021, from https://www.trafikverket.se/nara-dig/Vastra-gotaland/vi-bygger-och-forbattrar/Vastlanken---smidigare-pendling-och-effektivare-trafik/

University of Colorado Boulder. (2016, August 8). Immunization with bacteria promotes stress resilience, coping behavior in mice. CU Boulder Today. Retrieved from https://www.colorado.edu/today/2016/05/16/immunization-bacteria-promotes-stress-resilience-coping-behaviors-mice-cu-boulder-study [consulted 2021, April 22]

World Health Organization. (n.d.).
Housing and health. World Health Organisation, Regional Office for Europe. Retrieved from https://www.euro.who.int/en/health-topics/environment-and-health/Housing-and-health/housing-and-health# [21/02/12]

BIBLIOGRAPHY

Boltshauser, R., Kamm, T., Kapfinger, O. et al. (2011)
Haus Rauch. Birkhäuser Edition, Basel.

Fontaine, L., & Anger, R. (2009).
Bâtir en terre, du grain de sable à l'architecture. Belin.

Hall M.-R, Lindsay R., Krayenhoff M (2012)
Modern earth buildings, Materials, engineering, construction and application. Woodhead Publishing Limited, 2012

Heringer A., Howe L.-B, Rauch Martin (2019)
Upsacling Earth. Material, process, catalyst
gta Verlag, ETH Zurich, Institute for the History and Theory of Architecture

Minke, G. (2009)
Building with earth, Design and Technology of a sustainable Architecture.
Second Edition, Birkhäuser Edition

Röhlen, U., Ziegert, C., & Mochel, A. (2013).
Construire en terre crue, Construction - Rénovation - Finitions.
Editions Le Moniteur.

Nilson, P.-E. (2003)
Achieving the desired indoor climate, energy efficiency aspects of system design. Studentlitteratur

PUBLICATIONS

Basecq, V. (2016)
Développement d'un mur capteur-stockeur solaire pour le chauffage des bâtiments à très basse consommation d'énergie

Calderon R., Ryberg A., (2021, January)
Klimatarbete Hoppet, Delrapportering systemskede.
Derome, *Retrieved from : https://goteborg.se/wps/wcm/connect/fd40a939-15db-4e3a-b249-0427c4d87a13/Klimatarbete+i+Hoppet+-+Delrapportering+systemskede.pdf?MOD=AJPERES&CONVERT_TO=url&CACHEID=ROOTWORKSPACE-fd40a939-15db-4e3a-b249-0427c4d87a13-nwqVSv-*

City of Gothendurg. (2015, January).
Climate program for Gothenburg. Environmental and Climate Committee. Retrieved from : https://goteborg.se/wps/wcm/connect/7ba2b573-9216-4bb9-8a1f-0915b40ce4b5/Climate+program+för+Gothenburg.pdf?MOD=AJPERES

Global ABC, International Energy Agency and the UNEnvironment (2019)
2019 global status report for buildings and construction: Towards a zero-emission, efficient and resilient buildings and construction sector. Retrieved from : https://webstore.iea.org/download/direct/2930?filename=2019_global_status_report_for_buildings_and_construction.pdf

Joana Eid, (2019)
Élaboration d'un éco-géo-matériau à base de terre crue
Retrieved from https://tel.archives-ouvertes.fr/tel-02073671/file/EID.pdf

Matsdotter, V (2020)
Down to earth, Circular materials flow // Ressource salvation
Master thesis, Chalmers University of Technology, design for sustainable development.

Niras Arckitekten, SKL. (2019, November)
Bilaga 8 - Funktionsprogram rev.3 for SKL Upphandling Förskolebyggnader Retrieved from : https://www.sklkommentus.se/globalassets/inkopscentral/upphandling/forskolebyggnader-2018/funktionsprogram-rev3-2019-11-28-version-lagre-upplosning.pdf

Office fédéral de l'energie (2002).
Catalogue d'élément de construction avec calcul de la valeur U
Retrived from : https://fdocuments.fr/document/catalogue-delements-de-construction-avec-calcul-de-la-valeur-u-.html

Skolverket. (2019).
Curriculum for the Preschool - Lpfö 18.
Norstedts Juridik AB.
Retrived from : https://www.skolverket.se/download/18.6bfaca-41169863e6a65d897/1553968298535/pdf4049.pdf2019

(SGI) Swedish Geotechnical Institute (2004)
SGI report n°65, Quick Clay in sweden
Linköping 2004. Retrieved from : https://www.sgi.se/globalassets/publikationer/rapporter/pdf/sgi-r65.pdf)

UN Environment and International Energy Agency (2017):
Towards a zero-emission, efficient, and resilient buildings and construction sector. Global Status Report 2017.
Retrieved from https://www.worldgbc.org/sites/default/files/UNEP%20188_GABC_en%20%28web%29.pdf

Van Damme, H. (2013, January).
CRAterre : *La terre, un béton d'argile*. Pour La Science N°423, 423.
http://craterre.org/diffusion:articles/view/

OTHER MEDIA

Gauzin-Müller D. (2020, november)
Metamorphoser l'acte de construire, Frugalité heureuse et créative : *Vers un nouveau vernaculaire : bois, terre, paille, pierre & co.*
Retrieved from :
https://www.youtube.com/watch?v=rX_exsmrM3w

Karstunen M. (2019)
William Chalmers Lecture - Chalmers University of Technology, Sweden
Gothenburg Clay – the foundation of the Future.
Retrieved from : https://www.youtube.com/watch?v=1XcYTMyojwQ

Loiret P.-E., Crête E., Misse A. et al. (2020, december 10th)
Webinar : *Construire avec les matériaux cycle terre*
Retrieved from :
https://www.cycle-terre.eu/replay-webinar-01/

Steemers, K. (2021, Feb.)
DAB2020 Webinar, Future Perspectives : *Health and Well Being*

IMAGE LIST

IMAGE

Image 2 ©Link Arkitektur, n.d
Retreived from https://linkarkitektur.com/en/Projects/Foerskolan-Hoppet?sp=

Image 3 ©M. Roe, Mineralogical Society, n.d
Retrieved from https://www.minersoc.org/images-of-clay.html

Image 13 ©amàco, n.d. Retreived from https://amaco.org/curve-six-assises-en-pise/

Image 14 ©Didier Jordan, Ville de Genève, n.d
Retrieved from https://www.espazium.ch/fr/actualites/le-pavillon-geisendorf-ne-du-sol-genevois

Image 15 ©Luc Boegly, (n.d)
Retrieved from https://www.nunc.fr/centre-d-interpretation-du-patrimoine-archeologique-de-Dehlingen-67-169.html

Image 16 & Image 17 ©Markus Bhüler, (2013-2014)
Retrieved from http://www.buehler-fotograf.ch/buchprojekte#/urban/

Image 18 ©Adolf Bereuter (n.d)
Retrieved from https://www.dachverband-lehm.de/bauwerke/vorarlberg-museum-bregenz

Image 19, Image 20, Image 22, Image 23 ©Beat Bühler, 2011 in Boltshauser, R., Kamm, T., Kapfinger, O. et al. (2011)*Haus Rauch*. Birkhäuser Edition, Basel.

Image 21 © Albrecht Imanuel Schnabel
Retrieved from https://www.albrecht-schnabel.com/privat/lehmhaus

Image 24 ©Terrabloc

Image 25 ©Ralf Freiner(n.d.) Retrieved from http://terra-award.org/project/stable-plazza-pintgia/?lang=fr

Image 26 ©Andrew Avdeenko (n.d). Architect: Ryntovt
Retrieved from : https://ryntovt.com/en/works/ekootel-friend-house/

Image 27 ©Didier Jordan. Architect : David Reffo
Retrieved from : http://www.terrabloc.ch/geisendorf

Image 28 & Image 28 ©Elettra M.,Building trust international. AD Editorial Team, (Jul 2017) *Workshop in Italy Constructs Rammed Earth Structures to Rescue Constructive Traditions*. ArchDaily. Accessed 31 Mar 2021. <https://www.archdaily.com/874193/workshop-in-italy-raises-rammed-earth-structures-to-rescue-constructive-traditions> ISSN 0719-8884

Image 30 ©Gernot Minke, 2009 in Minke, G. (2009) *Building with earth, Design and Technology of a sustainable Architecture*. Second Edition, Birkhäuser Edition

Image 31 ©Photo : Iwan Baan. Retrived from : https://iwan.com/portfolio/ricola-krauterzentrum-laufen-switzerland/#13489

Image 32 ©Wasp, Retrieved from :https://www.3dwasp.com/en/3d-printed-house-tecla/

Image 33 ©Walter Unterrainer

Image 34 ©Springer International Publishing Switzerland 2016. Retrieved from https://link.springer.com/chapter/10.1007/978-3-319-19491-2_4

Image 35© Région Nouvelle-Aquitaine, Inventaire général du patrimoine culturel – Baptiste Quost , 2012)
Original name : Détail des rouleaux de torchis en sous-face du plancher du couvert dans une maison de Monpazier (Dordogne).

Image 36 Adapted from Minke , G., (2009). *Building with earth*. Birkhäuser Edition, Basel.

Image 37 © Luc Floissac
Retrieved from http://www.areso.asso.fr/spip.php?article406

Image 38 © Bruno Klomfar.
Retrieved from : https://www.lehmtonerde.at/en/products/product.php?aID=109

Image 39 ©Terrabloc. Retrieved from : http://www.terrabloc.ch/chateau-de-bardonnex

Image 40 ©Lehmag AG . Retrieved from : https://lehmag.ch/fr/projekt/wohnen-hbs-26-zuerich-2019/

Image 41 ©Photograph : Stefano Mori. Architects : Anna Heringer and Marting Rauch. Retrieved from https://divisare.com/projects/427472-anna-heringer-martin-rauch-stefano-mori-omicron-relaxing-spaces

Image 43 ©Ecolut, Retrieved from https://www.dachverband-lehm.de/images/2x/75.jpg

Image 44 ©Walter Unterrainer

Image 45 ©Michel Denancé (n.d). Architect : Maurer Architectes.
Retrieved from : https://www.maurer-architecture.com/maurer-et-gilbert-architectes_projet__Batiment-16_14.htm

Image 46 ©Amàco. Retrieved from https://media-exp1.licdn.com/dms/image/C4E22AQEdyM0rWPt3zw/feedshare-shrink_2048_1536/0/1617012804377?e=1622073600&v=beta&t=Lc-Mt4b98HdnXxt-jx6eCyZ_hEUI25SBhj3rAroMEOw

Image 47 ©Photo : Amàco, architect : Atelier Philip Madec. Retrieved from the movie “films du lierre”, available at : https://www.youtube.com/watch?v=4pJsckTHjV0

Image 48 ©Photo: Andy Harris , Architecte : Gernot Minke. Retrieved from http://gernotminke.gernotminke.de/projects/

Image 49 ©Daniel duchert. Retrieved from https://www.lehm-design-raum.de/de/innenarchitektur/

FIGURE LIST

FIGURE

Figure 1 : Evolution of the distribution of the carbon footprint in buildings
Data from Architecture 2030 (n.d) Retreived from : https://architecture2030.org/new-buildings-embodied/ and UN environmental status report 2017

Figure 2 : Embedded carbon in different materials
Adapted from Pradenic, H. (2020). *Une empreinte environmental si légère*. Maisons Paysannes de France, 2016, p.17. Retrieved from : https://fr.calameo.com/read/0029750202c618a74298e [2021/04/23]

Figure 3 : Amount of extracted earth in the Västlanken project
By the author, Data from Sampson, A. (2015). Stockholm City Hall. retrieved from Sweden.Org.Za. https://www.sweden.org.za/stockholm-city-hall.html

Figure 7 : Earth construction around the world
Adapted from Fontaine, L. et Anger, R. (2009)
Bâtir en terre, du grain de sable à l'architecture. Belin.

Figure 8 : Time line of earth construction
By the author, Data from Fontaine, L. et Anger, R. ,(2009) - Minke, G. (2009) - Röhlen, U., Ziegert, C., & Mochel, A. (2013))

Figure 9 *:* Earth characterization
Adapted from Minke , G., (2009). *Building with earth*. Birkhäuser Edition, Basel.

Figure 10 *:* Basic units and primary lamellas formation of Illite clay
Data from Minke , G., (2009). *Building with earth*. Birkhäuser Edition, Basel.

Figure 11: Particle of Illite clay made of several elementary structures
Adapted from L. W. Diamond (2008), retreived from https://www.researchgate.net/publication/23558330_Translational_diffusion_of_water_and_its_dependence_on_temperature_in_charged_and_uncharged_clays_A_neutron_scattering_study/figures?lo=1

Figure 12 : Geological map of Göteborg
By Sveriges Geologiska Undersökning SGU Retrieved from www.sgu.se

Figure 13 *: Illite properties*
Compiled Data from Minke , G., (2009). *Building with earth*. Birkhäuser Edition, Basel , Röhlen, U., Ziegert, C., & Mochel, A. (2013). *Construire en terre crue, Construction - Rénovation - Finitions.* Editions Le Moniteur. & (SGI) Swedish Geotechnical Institute (2004) *SGI report n°65, Quick Clay in sweden* Linköping 2004.

Figure 14 : Vitruvian principle of architecture and indoor climate
Adapted from K.Steemers, 2021 DAB2020 Webinar, Future Perspectives : *Health and Well Being*

Figure 15 : Physical parameters of indoor climate and domains of action of the earth
By the author, data from WHO , retrieved from https://www.uib.no/en/hms-portalen/79904/indoor-climate#:~:text=The%20indoor%20climate%20is%20made,and%20volume%20of%20fresh%20air*)*

Figure 16 : Thermal comfort parameters
By the author, Data from Nilsson P.-E., 2003

Figure 18 - Figure 19 : Optimal operative temperature & Acceptable comfort zone
Adapted from Fanger, P.O. (1970) *Thermal Comfort*. Danish Technical Press. Copenhagen.

Figure 20 *:* Thermal unit
Data from Office fédéral de l'énergie, 2002 in *Catalogue d'éléments de construction avec calcul de la valeur U*
Retrieved from https://www.vd.ch/fileadmin/user_upload/themes/environnement/energie/fichiers_pdf/catalogue_elements_assainis.pdf

Figure 21 *:* Lambda value of different materials
Adapted from R. Camponovo 2016, Building Thermal, HEPIA - Personal communication

Figure 23 *:* Relative humidity depending on the temperature and the water content in the air. Adapted from Minke , G., (2009). *Building with earth*. Birkhäuser Edition, Basel.

Figure 24 *:* Average relative humidity in Göteborg in 2019
adapted from weather-and-climate.com 2019, retrieved from https://www.weather-and-climate.com/average-monthly-Rainfall-Temperature-Sunshine,gothenburg-vastra-gotaland-se,Sweden

Figure 25 *:* Humidity and health
Adapted from Arundel et al., 1985, *Criteria for Human Exposure to Humidity in Occupied Buildings*)

Figure 26 *:* Absorption curves of 15mm thick samples, one side exposed, at 21°C after a sudden rise in humidity from 30% to 70%. *(adapted from Minke G., 2009, Building with earth*. Birkhäuser Edition, Basel)

Figure 27 : Sources of indoor air pollutants
Adapted from D. Y. C. Leung, 2015, retrieved from https://www.researchgate.net/publication/272390698_Outdoor-indoor_air_pollution_in_urban_environment_Challenges_and_opportunity/figures?lo=1

Figure 28 *:* Sound behavior (Author, adapted from Juguin T., April 2018, Buildings acoustics, HEPIA , Personal communication)

Figure 30 : Reduction of electromagnetic radiation
Adapted from Minke , G., (2009). *Building with earth*. Birkhäuser Edition, Basel.

Figure 32 *:* From linear to circular
Adapted from Circular Flanders, 2017 Retrieved from : https://vlaanderen-circulair.be/en/infographics

Figure 36 - Figure 38 *:* Project section, D. Reffo Architecte in Le pavillon Geisendorf: né du sol genevois. (2019). Tracé, 22. https://static1.squarespace.com/static/56f11c090442628377d7f98e/t/5e8b28f21e80797db50bf60f/1586178296262/TracesNov2019.pdf

Figure 40 - Figure 41 : First plan ans Section
Adapted from Nunc Alsace Architectes, retrieved from : https://www.nunc.fr/centre-d-interpretation-du-patrimoine-archeologique-de-Dehlingen-67-169.html

Figure 44 - Figure 45 *: Adapted from Arquitectura Viva, n.d. retreived*
May 7, 2021 from : https://arquitecturaviva.com/works/edificio-ricola-krauterzentrum-2

Figure 47 - Figure 48 *:* Section & Plan *, Cukrowicz Nachbaur Architekten, retrieved from : https://www.dachverband-lehm.de/bauwerke/vorarlberg-museum-bregenz*

Figure 50 *:* Clay based materials
data from Boltshauser, R., Kamm, T., Kapfinger, O. et al. (2011) *Haus Rauch*. Birkhäuser Edition, Basel.

Figure 52 : Haus House thermal and relative humidity average on one year operation
Data from Boltshauser, R., Kamm, T., Kapfinger, O. et al. (2011)*Haus Rauch*. Birkhäuser Edition, Basel.
Drawing adapted from : Bauhandwerk, 2011, *Kontrollierte Erosion im Lehmbau and* Retrieved from : https://www.bauhandwerk.de/artikel/bhw_Kontrollierte_Erosion_im_Lehmbau_1176521.html

Figure 53 *:* Rauch house walls and floors type
Adapted drawing and date from Boltshauser, R., Kamm, T., Kapfinger, O. et al. (2011)*Haus Rauch*. Birkhäuser Edition, Basel

Figure 54 *:* Wheel of techniques
Adapted from CRATerre, 1994. In. HOUBEN, H, GUILLAUD, H, 1994. *Earth construction: a comprehensive guide*. Londres: IT Publications. 362 p. ISBN 1-85339-193-X

8

Appendix

APPENDIX A

ECHANTILLON C1 - CENTRAL STATION

Appearance
- Stiff
- Grey slightly turquoise
- Red inclusion (iron)

Smell :
- Presence of organic components

Ball form test and ball drop:
- Plastic behavior

Cutting test :
- Very small grain up to 1mm
- Slightly shiny surface

Wash test :
- Clay washed relatively quickly

Lime content:
- Natural lime content

Salt content :
- 0.1 % chloride
- 0.25% sulphate
- 0.06% nitrate

Binding force:
- Upper part of “Almost fat” classification

Characterization :
- Clayey silt

Evaluation + :
- Cohesive properties are sufficient to produce any kind of earth material

Evaluation - :
- High presence of organic components that can’t be eliminated
- High amount of salt, that can be eliminated

Conclusion :
- Not recommended to use because of the organic components

ECHANTILLON C2 - OLSKROKEN

Appearance :
- Soft plastic
- Light grey
- No specific inclusion Smell :

Smell:
- Presence of minimal organic components

Ball form test and ball drop :
- Plastic behavior

Cutting test :
- Very small grain up to 1mm
- Slightly shiny surface

Wash test:
- Clay washed relatively quickly

Lime content:
- Natural lime content

Salt content :
- 0.34% Chloride
- 0.45% Sulphate
- 0.02% Nitrate

Binding force:
- Middle part of “Almost fat” classification

Characterization :
- Clayey silt

Evaluation + :
- Cohesive properties are sufficient to produce any kind of earth material

Evaluation - :
- High amount of salt , that can be eliminated following a specific processes

Conclusion :
- The usage of C2 is recommended but further test would be needed in a second step.

Data from : ZRS Ingenieure GmbH report, Prof. Dr.-Ing. Christof Ziegert, Personal communication, 01.09.2019

APPENDIX B

TEST DESCRIPTION

Smell test :

Smell a loam sample. A loam to be used in building should be composed only by minerals and therefore have less smell as possible. Odors in the loam indicates organic compounds and lead to complication as a building materials.

Dry hand test :

Feel and touch the dry loam. Try to break the bigger aggregate, if it's hard there is probably an important amount of clay (if it is not a gravel !) A disagreeable grain feeling indicates a sandy composition, it is more agreeable if it is mostly silt. Finally clayey soil would be sticky, smooth or floury.

Humid hand test :

Add water to the previous sample (dry hand test), to bring it in a humid state. If the bigger aggregates take time to become smooth there is probably an important amount of clay.

Footprint test :

Adding water to the previous sample to bring it in a plastic state. Form a ball and make a hole with the thumb, adding water in it, and see how quickly the water level decrease. The more time it takes, the more clay there is.

Washing hand test :

From the previous plastic state, add water until it become viscous. From there, with a small water jet (plastic bottle with hole in the cap) clean the hand with small jet pressure. The clay will be evacuated with water and the aggregates will be cleaned from it. What remains in the hand after the process give an idea of the kind of aggregates present in the soil.

Cutting test :

Form a ball with loam in a plastic state. Cut the ball in half. If the surface is shiny : there is a high clay content, on the opposite if the surface is dull it is a mainly a mix of silt.

Sedimentation test :

Fill a bottle with 1/4 earth and 3/4 water, mix it and let the particle settle down for 24h. It helps to know more or less the proportion of each particles

Ball dropping test:

Form a ball in a plastic state and drop it 1.5m. Different results show different cohesive properties of clay. The test was done several times, for different amounts of water and different compositions to try to find the optimal situation. A ball that has no cracks has a high bond strength and often needs to be mixed with sand (to reduce shrinkage). If the ball disintegrates entirely, the cohesive properties are not good enough to be used in construction.

Swelling and shrinking test

In a round mold 5 cm in diameter and 1 cm high, form an earth tablets. Remove the mold and let it dry for 24 hours, turn it over and let it dry for another 48 hours. When properly dried, put the mold back in place and see if the shrinkage is visible, measure and compare to the original size.

Ball in water test

Form a ball in a plastic state and put it in a glass filled with water. Measure the time it takes to collapse. Depending on the composition and potential additives, it will take a different time to decompose, the longest it takes the more water resistant it is.

Cohesion test

In the plastic state, form cigar shapes 2cm thick and twenty centimeters long. Put it horizontally on a table, and make them protrude more and more into the void until it breaks. Lets see which mixture is the most cohesive. Measure the fallen parts, the longest and the strongest cohesion.

Data from Minke, G. 2009 & Amàco, retrieved from https://craterre.hypotheses.org/3735

APPENDIX C

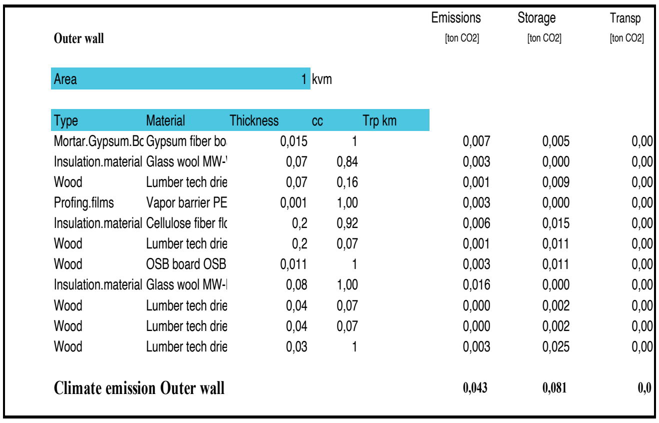
INVENTORY		DESCRIPTION														NEED								
N°	Room	Floor		Orientation					Type						Thermal confort		Atmospheriq		Actini	coustique conf		Other need	
		GF	1st	S	W	N	E	No W.	Circ.	Tec/su	Kit.	Staff	Com.	Unit	Temperature	Humidity	Polution	Air Quality	Magnetic field	inside sound	outside sound	cleanability	mechanical resistance
A102	Passage	x						x	x						=	=	=	=	-	=	+	+	+
A103	Storage	x						x		x					-	=	/	-	-	/	/	=	=
A104	Electricity	x						x		x					/	/	/	/	/	/	/	/	/
A105	Kök	x		x	x						x				=	+	+	+	-	+	+	+	=
A106	Diskrum	x						x			x				=	+	=	=	-	=	+	+	=
A107	storage	x						x			x				-	=	/	-	-	/	/	=	=
A108	Fridge	x						x			x				/	/	/	/	/	/	/	/	/
A109	Freezer	x						x			x				/	/	/	/	/	/	/	/	/
A110	Skrivplats	x			x						x				=	=	=	=	=	=	=	=	=
A111	Cleaning room	x						x			x				-	=	/	-	/	/	/	=	=
A112	Staff Changing room	x						x				x			+	+	=	=	-	+	=	+	-
A113	WC/D CR	x						x				x			=	+	=	+	-	=	+	+	=
A114	Central cleaning	x				x						x			-	=	/	-	/	/	/	=	=
A115	Staff entrance	x				x						x			=	=	=	=	-	=	+	+	+
A116	Elevator	x	x					x	x						/	/	/	/	/	/	/	/	/
A117	RWC/D staff	x						x				x			=	+	=	+	-	=	+	+	=
A118	Storage	x				x						x			-	=	/	-	-	/	/	=	=
A119	UC ?	x				x				x					/	/	/	/	/	/	/	/	/
A120	EL/TELE	x				x				x					/	/	/	/	/	/	/	/	/
A121	Atelié	x			x								x		+	+	+	+	=	+	+	+	+
A122	Multi activity room	x		x	x	x	x						x		+	+	+	+	=	+	+	+	+
A123	Atelié	x				x			x				x		+	+	+	+	=	+	+	+	+
A124	Staircase	x	x					x		x					=	=	=	=	-	=	+	+	+
A125	Storage	x						x							-	=	/	-	-	/	/	=	=
A129	Staircase	x	x					x	x			x			=	=	=	=	-	=	+	+	+
A130a	Entrance	x					x		x					x	=	+	=	=	-	=	+	+	+
A131a	Straircase	x	x				x		x					x	=	=	=	=	-	=	+	+	+
A132a	storage	x					x	x		x				x	-	=	/	-	-	/	/	=	=
A133a	Cloakroom	x						x						x	+	+	+	+	=	+	+	+	+
A134a	RWC/D	x						x						x	=	+	=	+	-	=	+	+	=
A135a	Classroom	x		x										x	+	+	+	+	+	+	+	=	=
A136a	Nap room	x		x			x							x	+	+	+	+	+	+	+	=	=
A137a	bathroom	x						x						x	=	+	=	+	-	=	+	+	=
A138a	WC	x						x						x	=	+	=	+	-	=	+	+	=
A139a	WC	x						x						x	=	+	=	+	-	=	+	+	=
A141a	Classroom	x				x								x	+	+	+	+	+	+	+	=	=
A142a	bathroom	x						x							=	+	=	+	-	=	+	+	=
A143a	WC	x						x							=	+	=	+	-	=	+	+	=
A144a	WC	x						x							=	+	=	+	-	=	+	+	=
A145a	Nap room	x				x	x								+	+	+	+	+	+	+	=	=
A146	EL	x						x		x				x	/	/	/	/	/	/	/	/	/
A130b	Entrance	x		x										x									
A131b	Staircase	x		x				x	x					x									
A132b	Storage	x						x		x				x									
A133b	Cloakroom	x						x						x									
A134b	RWC/D	x						x						x									
A135b	Classroom	x			x									x									
A136b	Nap room	x		x	x									x									
A137b	Bathroom	x						x						x									
A138b	WC	x						x						x									
A139b	WC	x						x						x									
A140b	Storage	x						x		x				x									
A141b	Classroom	x					x							x									
A142b	bathroom	x						x						x									
A143b	WC	x						x						x									
A144b	WC	x						x						x									
A145b	Nap room	x		x			x							x									
A146b	EL	x						x		x				x									
A201	Passage		x					x	x			x			=	=	=	=	-	=	+	+	+
A202	Changing room		x					x				x			+	+	=	=	-	+	=	+	-
A203	WC/D CR		x					x				x			=	+	=	+	-	=	+	+	=
A204	Tecnic		x					x		x					/	/	/	/	/	/	/	/	/
A205	Elec		x					x		x					/	/	/	/	/	/	/	/	/
A206	Cleaning room		x					x		x					-	=	/	-	/	/	/	=	=
A209	Office		x			x						x			+	+	+	+	+	+	+	=	=
A211	WC		x					x				x			=	+	=	+	-	=	+	+	=
A212	Call room		x			x						x			+	+	+	+	=	+	+	=	=
A213	Break room		x		x	x						x			+	+	+	+	=	+	+	=	=
A214	Meeting room		x		x							x			+	+	+	+	=	+	=	=	=
A215	KOP ?		x					x				x			-	=	/	-	-	/	/	=	=

Hoppet room need analysis. Source : personal analysis and survey to the stakeholders

APPENDIX D

FACADE SOUTH

LCA Hoppet

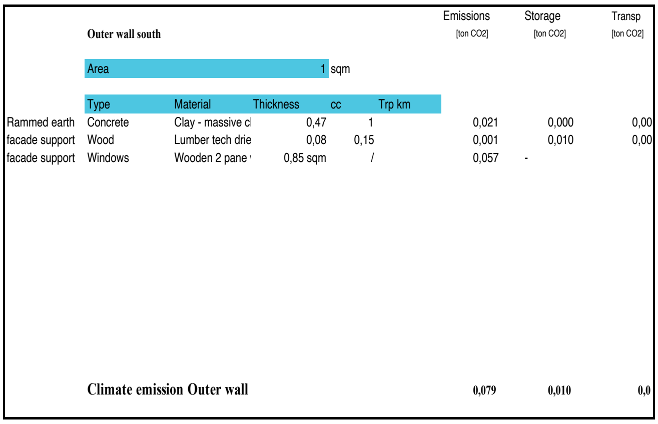


Outer wall

Area 1 kvm

Type	Material	Thickness	cc	Trp km	Emissions [ton CO2]	Storage [ton CO2]	Transp [ton CO2]
Mortar.Gypsum.Bc	Gypsum fiber bo	0,015	1		0,007	0,005	0,00
Insulation.material	Glass wool MW-'	0,07	0,84		0,003	0,000	0,00
Wood	Lumber tech drie	0,07	0,16		0,001	0,009	0,00
Profing.films	Vapor barrier PE	0,001	1,00		0,003	0,000	0,00
Insulation.material	Cellulose fiber flc	0,2	0,92		0,006	0,015	0,00
Wood	Lumber tech drie	0,2	0,07		0,001	0,011	0,00
Wood	OSB board OSB	0,011	1		0,003	0,011	0,00
Insulation.material	Glass wool MW-I	0,08	1,00		0,016	0,000	0,00
Wood	Lumber tech drie	0,04	0,07		0,000	0,002	0,00
Wood	Lumber tech drie	0,04	0,07		0,000	0,002	0,00
Wood	Lumber tech drie	0,03	1		0,003	0,025	0,00
Climate emission Outer wall					**0,043**	**0,081**	**0,0**

LCA Testbed



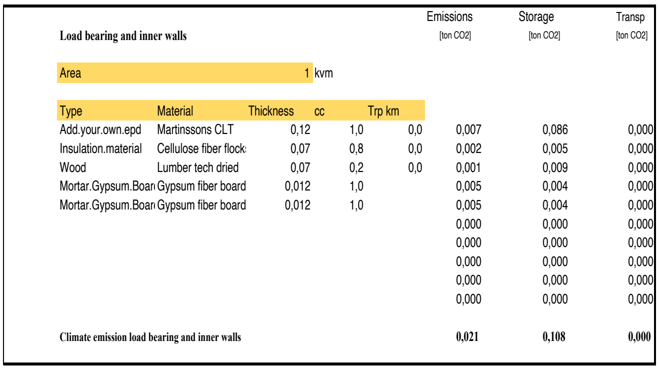
Outer wall south

Area 1 sqm

	Type	Material	Thickness	cc	Trp km	Emissions [ton CO2]	Storage [ton CO2]	Transp [ton CO2]
Rammed earth	Concrete	Clay - massive cl	0,47	1		0,021	0,000	0,00
facade support	Wood	Lumber tech drie	0,08	0,15		0,001	0,010	0,00
facade support	Windows	Wooden 2 pane '	0,85 sqm	/		0,057	-	
	Climate emission Outer wall					**0,079**	**0,010**	**0,0**

INNER WALL

LCA Hoppet

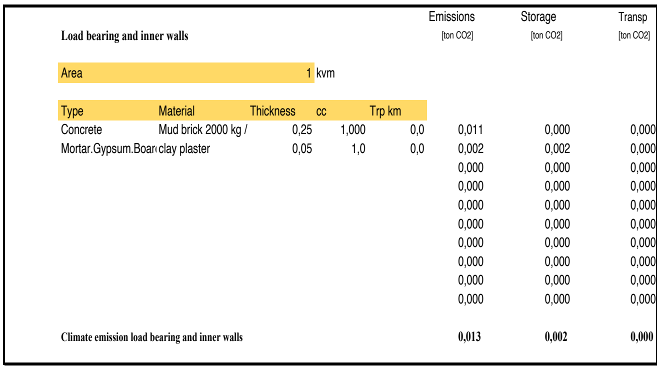


Load bearing and inner walls

Area 1 kvm

Type	Material	Thickness	cc	Trp km	Emissions [ton CO2]	Storage [ton CO2]	Transp [ton CO2]
Add.your.own.epd	Martinssons CLT	0,12	1,0	0,0	0,007	0,086	0,000
Insulation.material	Cellulose fiber flock	0,07	0,8	0,0	0,002	0,005	0,000
Wood	Lumber tech dried	0,07	0,2	0,0	0,001	0,009	0,000
Mortar.Gypsum.Boar	Gypsum fiber board	0,012	1,0		0,005	0,004	0,000
Mortar.Gypsum.Boar	Gypsum fiber board	0,012	1,0		0,005	0,004	0,000
					0,000	0,000	0,000
					0,000	0,000	0,000
					0,000	0,000	0,000
					0,000	0,000	0,000
					0,000	0,000	0,000
Climate emission load bearing and inner walls					**0,021**	**0,108**	**0,000**

LCA Testbed



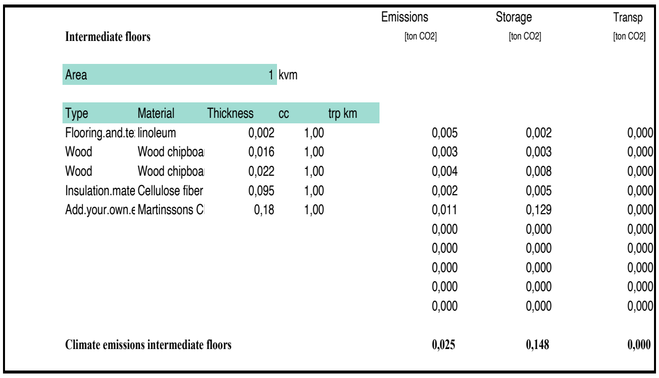
Load bearing and inner walls

Area 1 kvm

Type	Material	Thickness	cc	Trp km	Emissions [ton CO2]	Storage [ton CO2]	Transp [ton CO2]
Concrete	Mud brick 2000 kg /	0,25	1,000	0,0	0,011	0,000	0,000
Mortar.Gypsum.Boar	clay plaster	0,05	1,0	0,0	0,002	0,002	0,000
					0,000	0,000	0,000
					0,000	0,000	0,000
					0,000	0,000	0,000
					0,000	0,000	0,000
					0,000	0,000	0,000
					0,000	0,000	0,000
					0,000	0,000	0,000
					0,000	0,000	0,000
Climate emission load bearing and inner walls					**0,013**	**0,002**	**0,000**

INNER SLAB

LCA Hoppet

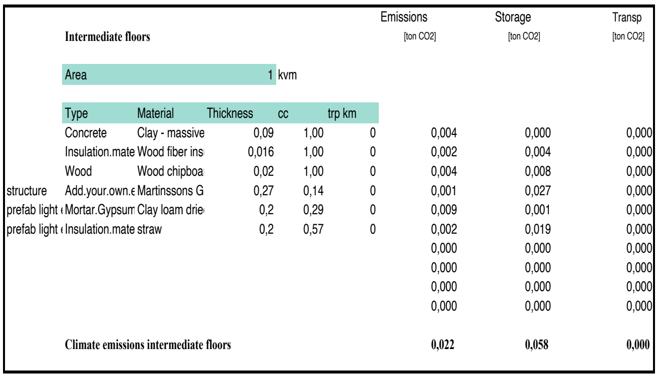


Intermediate floors

Area 1 kvm

Type	Material	Thickness	cc	trp km	Emissions [ton CO2]	Storage [ton CO2]	Transp [ton CO2]
Flooring.and.te	linoleum	0,002	1,00		0,005	0,002	0,000
Wood	Wood chipboa	0,016	1,00		0,003	0,003	0,000
Wood	Wood chipboa	0,022	1,00		0,004	0,008	0,000
Insulation.mate	Cellulose fiber	0,095	1,00		0,002	0,005	0,000
Add.your.own.e	Martinssons C	0,18	1,00		0,011	0,129	0,000
					0,000	0,000	0,000
					0,000	0,000	0,000
					0,000	0,000	0,000
					0,000	0,000	0,000
					0,000	0,000	0,000
Climate emissions intermediate floors					**0,025**	**0,148**	**0,000**

LCA Testbed



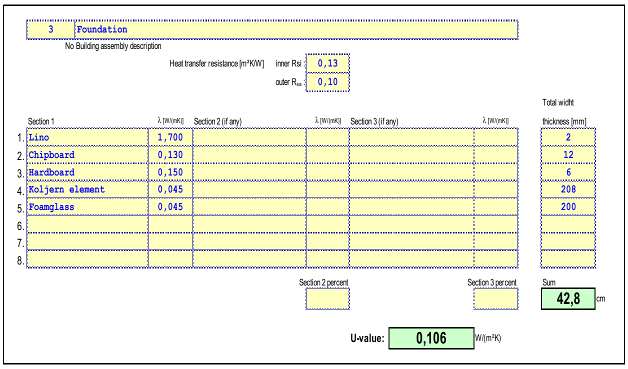
Intermediate floors

Area 1 kvm

	Type	Material	Thickness	cc	trp km	Emissions [ton CO2]	Storage [ton CO2]	Transp [ton CO2]
	Concrete	Clay - massive	0,09	1,00	0	0,004	0,000	0,000
	Insulation.mate	Wood fiber ins	0,016	1,00	0	0,002	0,004	0,000
	Wood	Wood chipboa	0,02	1,00	0	0,004	0,008	0,000
structure	Add.your.own.e	Martinssons G	0,27	0,14	0	0,001	0,027	0,000
prefab light (	Mortar.Gypsum	Clay loam drie	0,2	0,29	0	0,009	0,001	0,000
prefab light (	Insulation.mate	straw	0,2	0,57	0	0,002	0,019	0,000
						0,000	0,000	0,000
						0,000	0,000	0,000
						0,000	0,000	0,000
						0,000	0,000	0,000
	Climate emissions intermediate floors					**0,022**	**0,058**	**0,000**

GROUND SLAB

U-Value Hoppet



3 Foundation

No Building assembly description

Heat transfer resistance [m²K/W] inner Rsi : 0,13

outer R_{sa} : 0,10

	Section 1	λ [W/(mK)]	Section 2 (if any)	λ [W/(mK)]	Section 3 (if any)	λ [W/(mK)]	Total widht thickness [mm]
1.	Lino	1,700					2
2.	Chipboard	0,130					12
3.	Hardboard	0,150					6
4.	Koljern element	0,045					208
5.	Foamglass	0,045					200
6.							
7.							
8.							

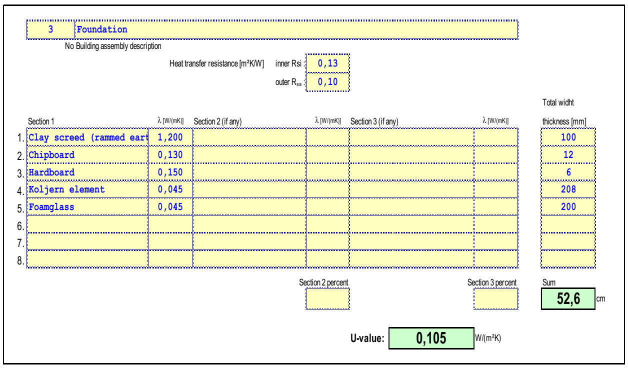
Section 2 percent

Section 3 percent

Sum 42,8 cm

U-value: 0,106 W/(m²K)

U-Value Testbed



3 Foundation

No Building assembly description

Heat transfer resistance [m²K/W] inner Rsi : 0,13

outer R_{sa} : 0,10

	Section 1	λ [W/(mK)]	Section 2 (if any)	λ [W/(mK)]	Section 3 (if any)	λ [W/(mK)]	Total widht thickness [mm]
1.	Clay screed (rammed eart	1,200					100
2.	Chipboard	0,130					12
3.	Hardboard	0,150					6
4.	Koljern element	0,045					208
5.	Foamglass	0,045					200
6.							
7.							
8.							

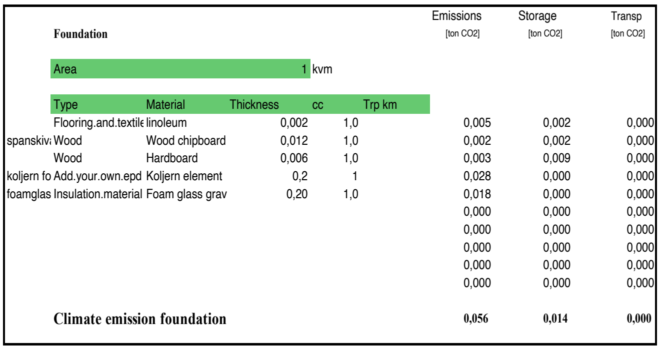
Section 2 percent

Section 3 percent

Sum 52,6 cm

U-value: 0,105 W/(m²K)

LCA Hoppet

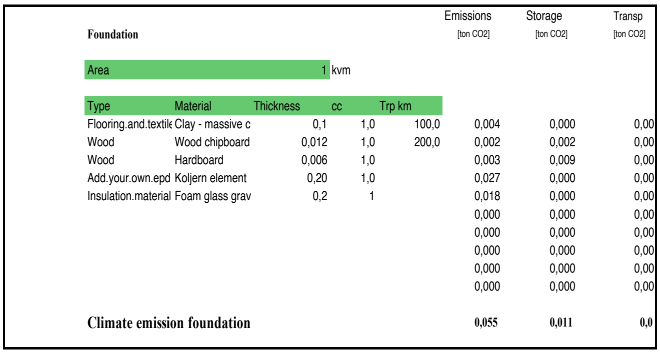


Foundation

Area 1 kvm

	Type	Material	Thickness	cc	Trp km	Emissions [ton CO2]	Storage [ton CO2]	Transp [ton CO2]
	Flooring.and.textile	linoleum	0,002	1,0		0,005	0,002	0,000
spanskiv	Wood	Wood chipboard	0,012	1,0		0,002	0,002	0,000
	Wood	Hardboard	0,006	1,0		0,003	0,009	0,000
koljern fo	Add.your.own.epd	Koljern element	0,2	1		0,028	0,000	0,000
foamglas	Insulation.material	Foam glass grav	0,20	1,0		0,018	0,000	0,000
						0,000	0,000	0,000
						0,000	0,000	0,000
						0,000	0,000	0,000
						0,000	0,000	0,000
						0,000	0,000	0,000
	Climate emission foundation					**0,056**	**0,014**	**0,000**

LCA Testbed



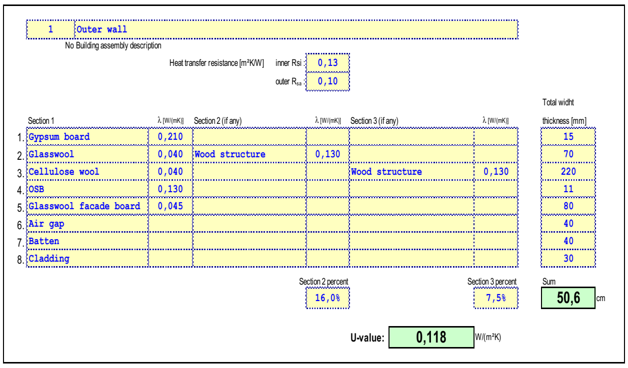
Foundation

Area 1 kvm

Type	Material	Thickness	cc	Trp km	Emissions [ton CO2]	Storage [ton CO2]	Transp [ton CO2]
Flooring.and.textile	Clay - massive c	0,1	1,0	100,0	0,004	0,000	0,00
Wood	Wood chipboard	0,012	1,0	200,0	0,002	0,002	0,00
Wood	Hardboard	0,006	1,0		0,003	0,009	0,00
Add.your.own.epd	Koljern element	0,20	1,0		0,027	0,000	0,00
Insulation.material	Foam glass grav	0,2	1		0,018	0,000	0,00
					0,000	0,000	0,00
					0,000	0,000	0,00
					0,000	0,000	0,00
					0,000	0,000	0,00
					0,000	0,000	0,00
Climate emission foundation					**0,055**	**0,011**	**0,0**

FACADE

U-Value Hoppet



1 Outer wall

No Building assembly description

Heat transfer resistance [m²K/W] inner Rsi : 0,13

outer R_{sa} : 0,10

	Section 1	λ [W/(mK)]	Section 2 (if any)	λ [W/(mK)]	Section 3 (if any)	λ [W/(mK)]	Total widht thickness [mm]
1.	Gypsum board	0,210					15
2.	Glasswool	0,040	Wood structure	0,130			70
3.	Cellulose wool	0,040			Wood structure	0,130	220
4.	OSB	0,130					11
5.	Glasswool facade board	0,045					80
6.	Air gap						40
7.	Batten						40
8.	Cladding						30

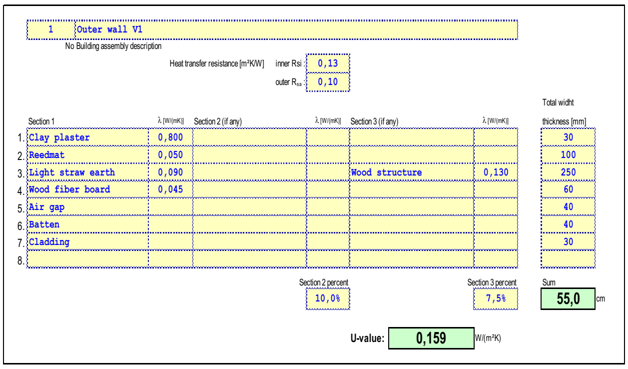
Section 2 percent 16,0%

Section 3 percent 7,5%

Sum 50,6 cm

U-value: 0,118 W/(m²K)

U-Value Testbed



1 Outer wall V1

No Building assembly description

Heat transfer resistance [m²K/W] inner Rsi : 0,13

outer R_{sa} : 0,10

	Section 1	λ [W/(mK)]	Section 2 (if any)	λ [W/(mK)]	Section 3 (if any)	λ [W/(mK)]	Total widht thickness [mm]
1.	Clay plaster	0,800					30
2.	Reedmat	0,050					100
3.	Light straw earth	0,090			Wood structure	0,130	250
4.	Wood fiber board	0,045					60
5.	Air gap						40
6.	Batten						40
7.	Cladding						30
8.							

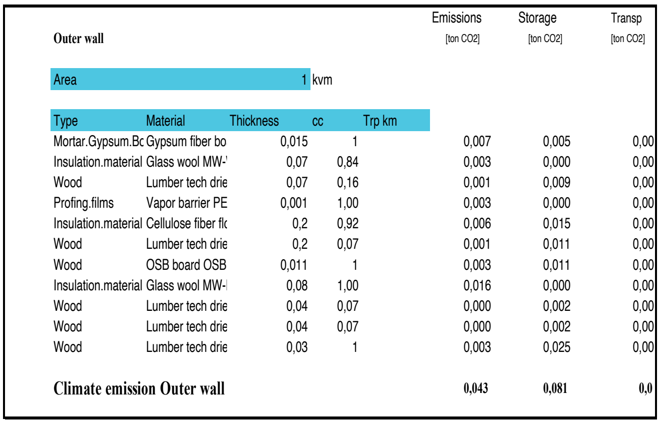
Section 2 percent 10,0%

Section 3 percent 7,5%

Sum 55,0 cm

U-value: 0,159 W/(m²K)

LCA Hoppet

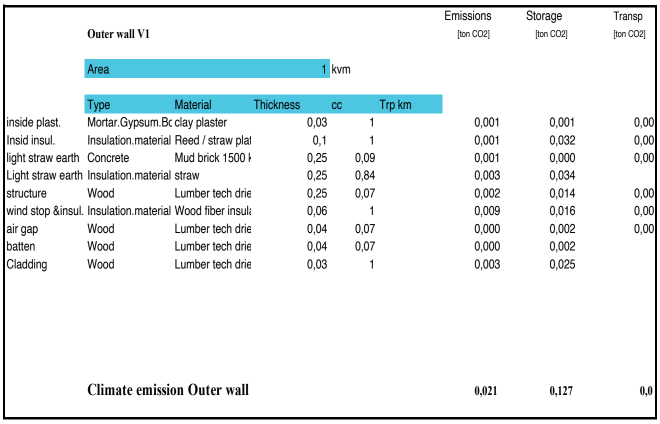


Outer wall

Area 1 kvm

Type	Material	Thickness	cc	Trp km	Emissions [ton CO2]	Storage [ton CO2]	Transp [ton CO2]
Mortar.Gypsum.Bc	Gypsum fiber bo	0,015	1		0,007	0,005	0,00
Insulation.material	Glass wool MW-'	0,07	0,84		0,003	0,000	0,00
Wood	Lumber tech drie	0,07	0,16		0,001	0,009	0,00
Profing.films	Vapor barrier PE	0,001	1,00		0,003	0,000	0,00
Insulation.material	Cellulose fiber flc	0,2	0,92		0,006	0,015	0,00
Wood	Lumber tech drie	0,2	0,07		0,001	0,011	0,00
Wood	OSB board OSB	0,011	1		0,003	0,011	0,00
Insulation.material	Glass wool MW-I	0,08	1,00		0,016	0,000	0,00
Wood	Lumber tech drie	0,04	0,07		0,000	0,002	0,00
Wood	Lumber tech drie	0,04	0,07		0,000	0,002	0,00
Wood	Lumber tech drie	0,03	1		0,003	0,025	0,00
Climate emission Outer wall					**0,043**	**0,081**	**0,0**

LCA Testbed



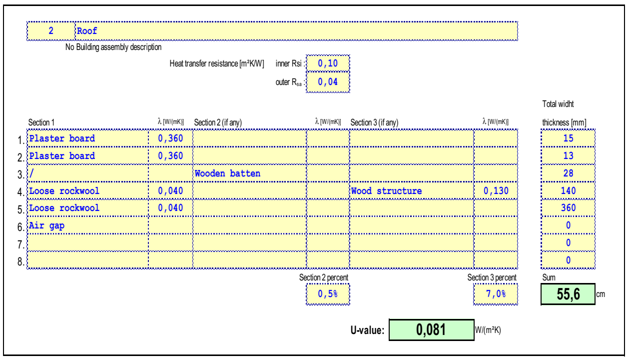
Outer wall V1

Area 1 kvm

	Type	Material	Thickness	cc	Trp km	Emissions [ton CO2]	Storage [ton CO2]	Transp [ton CO2]
inside plast.	Mortar.Gypsum.Bc	clay plaster	0,03	1		0,001	0,001	0,00
Insid insul.	Insulation.material	Reed / straw plat	0,1	1		0,001	0,032	0,00
light straw earth	Concrete	Mud brick 1500 k	0,25	0,09		0,001	0,000	0,00
Light straw earth	Insulation.material	straw	0,25	0,84		0,003	0,034	
structure	Wood	Lumber tech drie	0,25	0,07		0,002	0,014	0,00
wind stop &insul.	Insulation.material	Wood fiber insula	0,06	1		0,009	0,016	0,00
air gap	Wood	Lumber tech drie	0,04	0,07		0,000	0,002	0,00
batten	Wood	Lumber tech drie	0,04	0,07		0,000	0,002	
Cladding	Wood	Lumber tech drie	0,03	1		0,003	0,025	
	Climate emission Outer wall					**0,021**	**0,127**	**0,0**

ROOF

U-Value Hoppet



2 Roof

No Building assembly description

Heat transfer resistance [m²K/W] inner Rsi : 0,10

outer R_{sa} : 0,04

	Section 1	λ [W/(mK)]	Section 2 (if any)	λ [W/(mK)]	Section 3 (if any)	λ [W/(mK)]	Total widht thickness [mm]
1.	Plaster board	0,360					15
2.	Plaster board	0,360					13
3.	/		Wooden batten				28
4.	Loose rockwool	0,040			Wood structure	0,130	140
5.	Loose rockwool	0,040					360
6.	Air gap						0
7.							0
8.							0

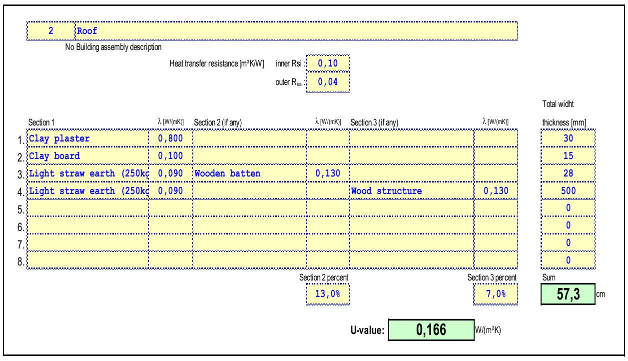
Section 2 percent 0,5%

Section 3 percent 7,0%

Sum 55,6 cm

U-value: 0,081 W/(m²K)

U-Value Testbed



2 Roof

No Building assembly description

Heat transfer resistance [m²K/W] inner Rsi : 0,10

outer R_{sa} : 0,04

	Section 1	λ [W/(mK)]	Section 2 (if any)	λ [W/(mK)]	Section 3 (if any)	λ [W/(mK)]	Total widht thickness [mm]
1.	Clay plaster	0,800					30
2.	Clay board	0,100					15
3.	Light straw earth (250kç	0,090	Wooden batten	0,130			28
4.	Light straw earth (250kç	0,090			Wood structure	0,130	500
5.							0
6.							0
7.							0
8.							0

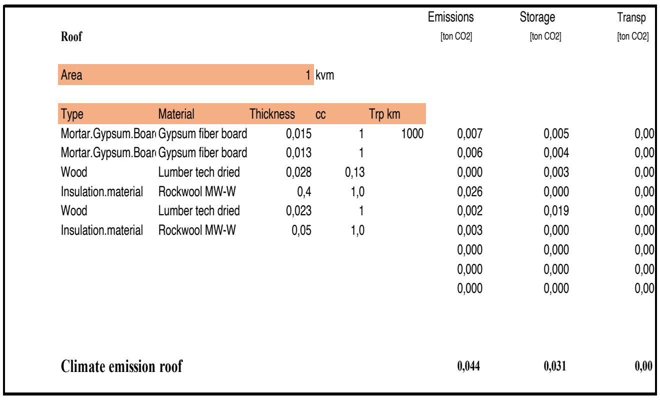
Section 2 percent 13,0%

Section 3 percent 7,0%

Sum 57,3 cm

U-value: 0,166 W/(m²K)

LCA Hoppet

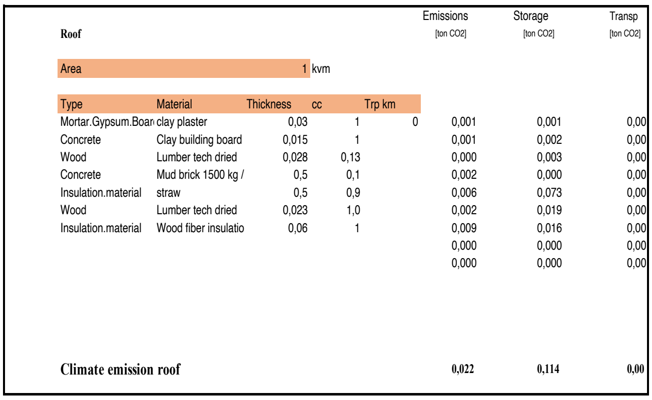


Roof

Area 1 kvm

Type	Material	Thickness	cc	Trp km	Emissions [ton CO2]	Storage [ton CO2]	Transp [ton CO2]
Mortar.Gypsum.Boar	Gypsum fiber board	0,015	1	1000	0,007	0,005	0,00
Mortar.Gypsum.Boar	Gypsum fiber board	0,013	1		0,006	0,004	0,00
Wood	Lumber tech dried	0,028	0,13		0,000	0,003	0,00
Insulation.material	Rockwool MW-W	0,4	1,0		0,026	0,000	0,00
Wood	Lumber tech dried	0,023	1		0,002	0,019	0,00
Insulation.material	Rockwool MW-W	0,05	1,0		0,003	0,000	0,00
					0,000	0,000	0,00
					0,000	0,000	0,00
					0,000	0,000	0,00
Climate emission roof					**0,044**	**0,031**	**0,00**

LCA Testbed



Roof

Area 1 kvm

Type	Material	Thickness	cc	Trp km	Emissions [ton CO2]	Storage [ton CO2]	Transp [ton CO2]
Mortar.Gypsum.Boar	clay plaster	0,03	1	0	0,001	0,001	0,00
Concrete	Clay building board	0,015	1		0,001	0,002	0,00
Wood	Lumber tech dried	0,028	0,13		0,000	0,003	0,00
Concrete	Mud brick 1500 kg /	0,5	0,1		0,002	0,000	0,00
Insulation.material	straw	0,5	0,9		0,006	0,073	0,00
Wood	Lumber tech dried	0,023	1,0		0,002	0,019	0,00
Insulation.material	Wood fiber insulatio	0,06	1		0,009	0,016	0,00
					0,000	0,000	0,00
					0,000	0,000	0,00
Climate emission roof					**0,022**	**0,114**	**0,00**

CHALMERS