# **EARTH**ARCHITECTURE

## BUILDING WITH RAMMED EARTH IN A COLD CLIMATE

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Master Programme Design for Sustainable Development
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2013
Master´s thesis

all the **new houses** are built for **energy consumption**, whereas our old houses are not

(Mrs. Indira Gandhi)

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David Martínez Escobar

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# ABSTRACT

Earth has been one of the most used building materials in the world. It is believed that today, one third of the world population lives in earthen houses.

But why we do not build with this material in our urban areas? What are the benefits and disadvantages when building with earth? This thesis is and exploration of rammed earth as building method, implemented in a cold climate. There are many prejudices against earth buildings, people might think that is not durable, but through case studies I will demonstrate that earth is reliable, if it is worked correctly, even in cold climates like in Sweden.

When we talk about earth building traditions, there are numerous methods and applications. This thesis focus in one: rammed earth, which is a mix of clay, sand and gravel, poured and compacted into a formwork, creating in this way monolithic elements. Rammed earth can be load-bearing, is good for sound insulation and the high heat capacity of the material serves as thermal mass.

My work is divided in two parts, the first one is the investigation, which includes case studies, experiments and analysis of earth´s physical characteristics. The second part is the design of an office building.

Earth constructions are commonly associated to small groups of builders and architects, concerned in environmental issues. Why do I think is important to develop these technologies in developed countries? I believe industrialized countries should embrace and develop alternative building technologies, and not the other way around where developing countries accept industrialized processes in construction.

# INTRODUCTION

# BACKGROUND

Imagine that you travel to Dr. Arroyo, a small town in the north of Mexico where temperatures can reach $38^{0}$ C during the day, and go down to $10^{0}$ C during the night. Here, in one of the rural areas, poor people have built with adobe bricks since colonization.

You are invited to have lunch with a family that lives in one of those adobe houses. The sun is directly over your head and it seems impossible, even to walk in the $38^{0}$ C heat. Finally, you arrive at the house; a small abandoned looking structure from the outside, the walls are leaning; the roof is low. The bricks have been damaged by erosion, showing the structures' age. As you enter you feel that the house is cool.

- *Smells good, tortillas, chile y frijoles*[1] *are served over the table* -. As you sit down and eat at a cracked oak table, you realize that the house is cool and there are no mechanical systems … - *how can this be possible?* -

1. Typical meal among poor mexican families

The air is so clean and feels so good for your lungs, there is something about the house that is difficult to explain.

You sit down by the shade in the doorway, “the best place in town” to feel the air flow between indoor and outdoor. You notice one person with his son preparing adobe bricks; clay, sand, straw … - *is that all they need?* - The kid starts to jump with naked feet over the loam when it had been wetted down. No machines? ... Does it not feel good?

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Dr. Arroyo is one of the poorest municipalities of Northern Mexico, most of the young people migrate to the United States in search for better opportunities. During my bachelor studies in Mexico I used to spend two weeks per year (Easter and Christmas), living in poor communities of Dr. Arroyo. The experience was not related to architecture but to a religious and social devotion to *live as equal*.

In Dr. Arroyo houses seem to mimic earth, as if they erupt directly from the ground. Adobes are made all year long. Here, people lack economical resources, nevertheless they do not depend on machines, companies, or money to build; the only thing they need is earth.

Unfortunately people is starting to leave behind these traditions, and the knowledge is getting lost, building with earth is becoming an “obsolete” technique. In Mexico the trend is to build a concrete house; durable, strong and reliable.

With a price of three Swedish crowns per piece of concrete block, people in Mexico can build houses in a fast and cheap way. It is not conceived that a beautiful and energy efficient home could be built with the material under our own feet.


Félix de Jesús Rentería and his family are delighted, after their house of wood and cartonboards was changed for a firm house of concrete floor and walls. (© 2012 Ahora Diario)

In 2012 the goverment of Durango, Mexico, started a program to substitute cartonboard houses for concrete houses.

The program is called “Sustitución de Casas de Cartón” (Substitution of Cartonboard Houses). Their goal is to provide poor families with homes where they can live with dignity (Diario 2012).

The program is good at first sight, the families used to live without basic services like water or electric light. With the new houses that has changed. But there are some things that people is not taking into account. The first thing is that concrete is presented as the best alternative, and is seen as symbol of prosperity and wealth. Concrete is not an evil material, but it is really the best solution for these houses?

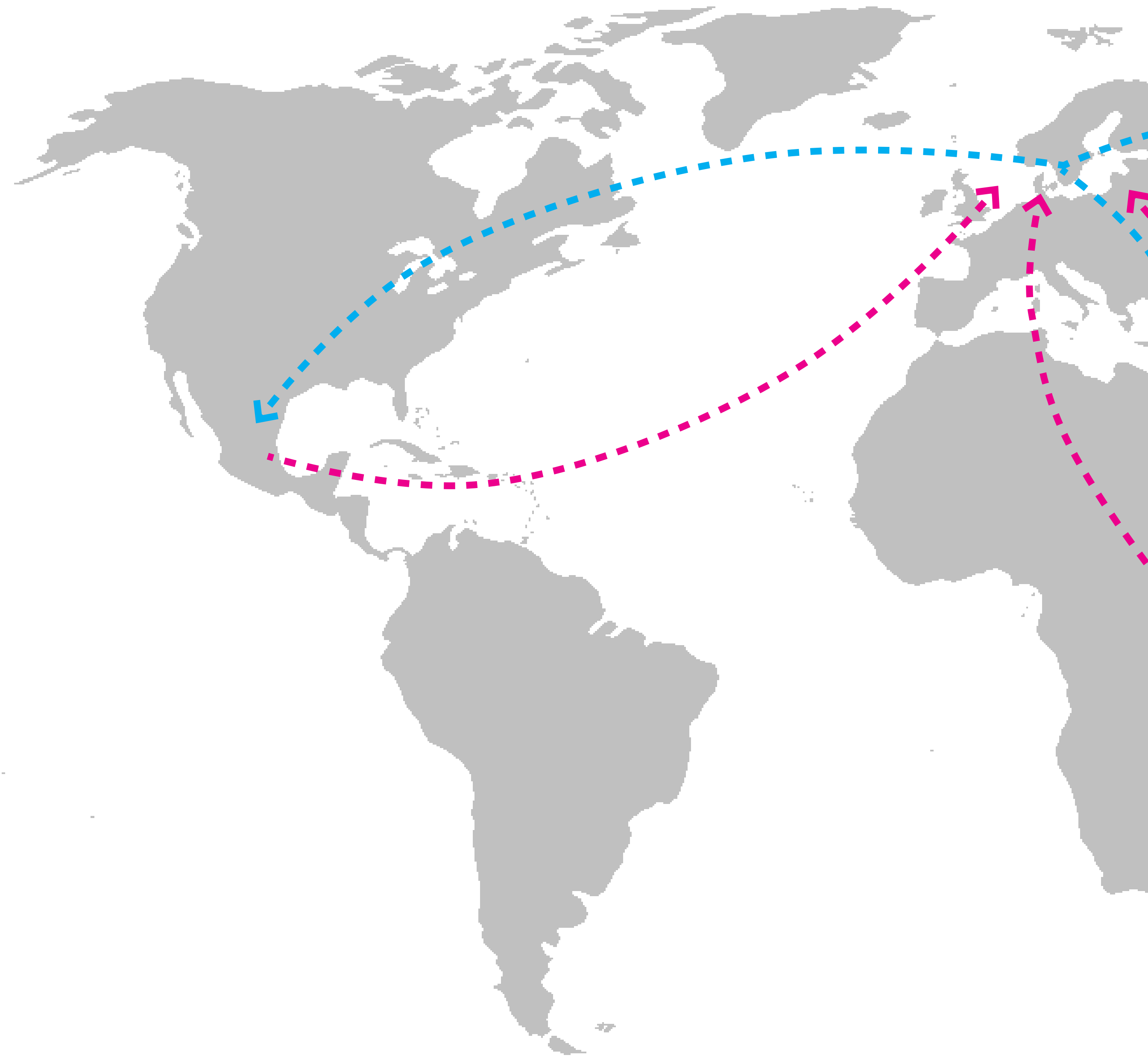
The second thing is that people is forgeting their own traditions. Abodes were used in Mexico, but today many mexicans wait for the goverment to “give” them a durable home of concrete blocks. People is not aware of their own heritage anymore, instead they are dependent of these type of programs to be able to “live with dignity”.

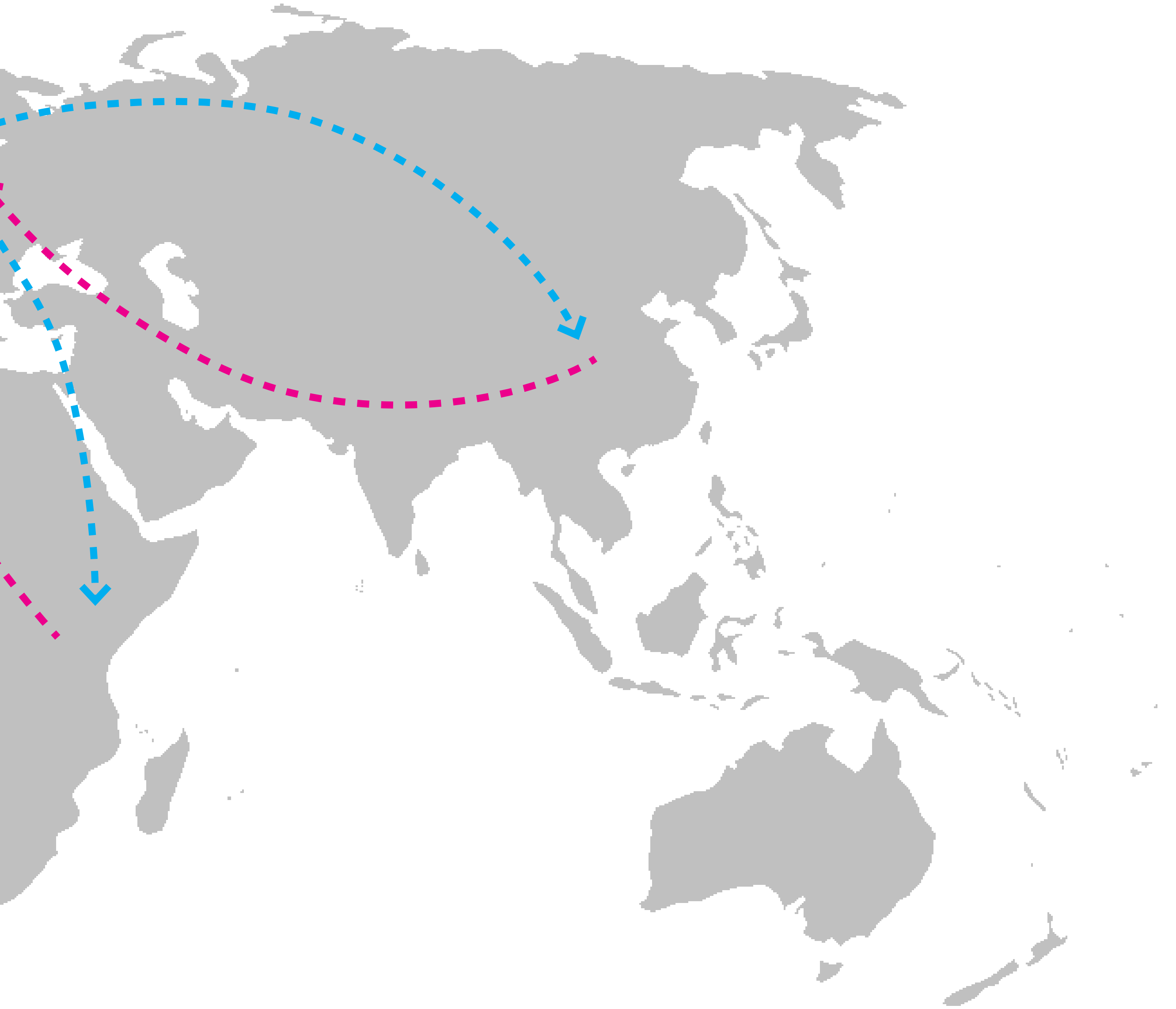
The advantages of building with earth go beyond the ecological characteristics of the material, there is a social impact.

Mexico is not the only example, other countries in Latin America are always looking to what developed countries are doing, adopting their technologies (in their own fashion).

This was the starting point for my thesis work. Instead of having a few coutnries dictating the guidelines of durable and relyable building materials, we could have a combination of vernacular buildings and new technologies.

Developing countries could re-discover their own traditions. Industrialized countries can improve building technologies in those traditions. In this way we ca have an interesting collaboration, while taking care of the planet.





Developing countries share knowledge about building with ntarual mateirals
Developed countries improve methods and building processes

The advantages of earth buildings are many, the most perceptible are perhaps the following ones:

-They are built with a local and natural material.
-They help to regulate indoor temperature and air humidity.
-They don´t use an excessive demand of energy to be constructed.

The threat of losing these building traditions is a problem that goes beyond the inmediate region. The global market allows developing countries to build with non-native materials in a convenient way.

In buildings that do not take in consideration the local climate, additional solutions like air conditioning need to be included. Situations like high energy demands, poor air quality and health compromises (Sick Building Syndrome) can be consequences of these type of buildings.

In addition to this the building sector faces problems like economical, ecological and social sustainability. The building industry has a big responsibility when talking about $CO_2$ Emissions.

## BUILDINGS ROLE IN $CO_2$ EMISSIONS

It is believed that even today, more than one third of the human population lives in houses built with earth (CRAterre 2009). But with the invention of Portland Cement in 1824, and Reinforced Concrete in 1849, man was able to create structures that weren´t even imaginable before that time. More important, cement technology has been standardized in a way that is easy (and energy demanding) to produce all over the world, giving it an advantage over other earthen building materials and making it hard to compete with new technologies.

**one third** of the human population resides in **earthen houses**
(Minke 2009)

According to IPCC (Intergovernmental Panel on Climate Change), global greenhouse gas (GHG) emissions due to human activities have grown since pre-industrial times, with an increase of 70% between 1970 and 2004. The largest growth in GHG emissions has come from energy supply, transport and industry, while the residential and commercial building, forestry and agriculture sectors have been growing at a lower rate.

Today the cement industry produces about 5% of global manmade $CO_2$ emissions, of which 50% is from the chemical process, and 40% from the burning of fuel. (Bennett 2010)

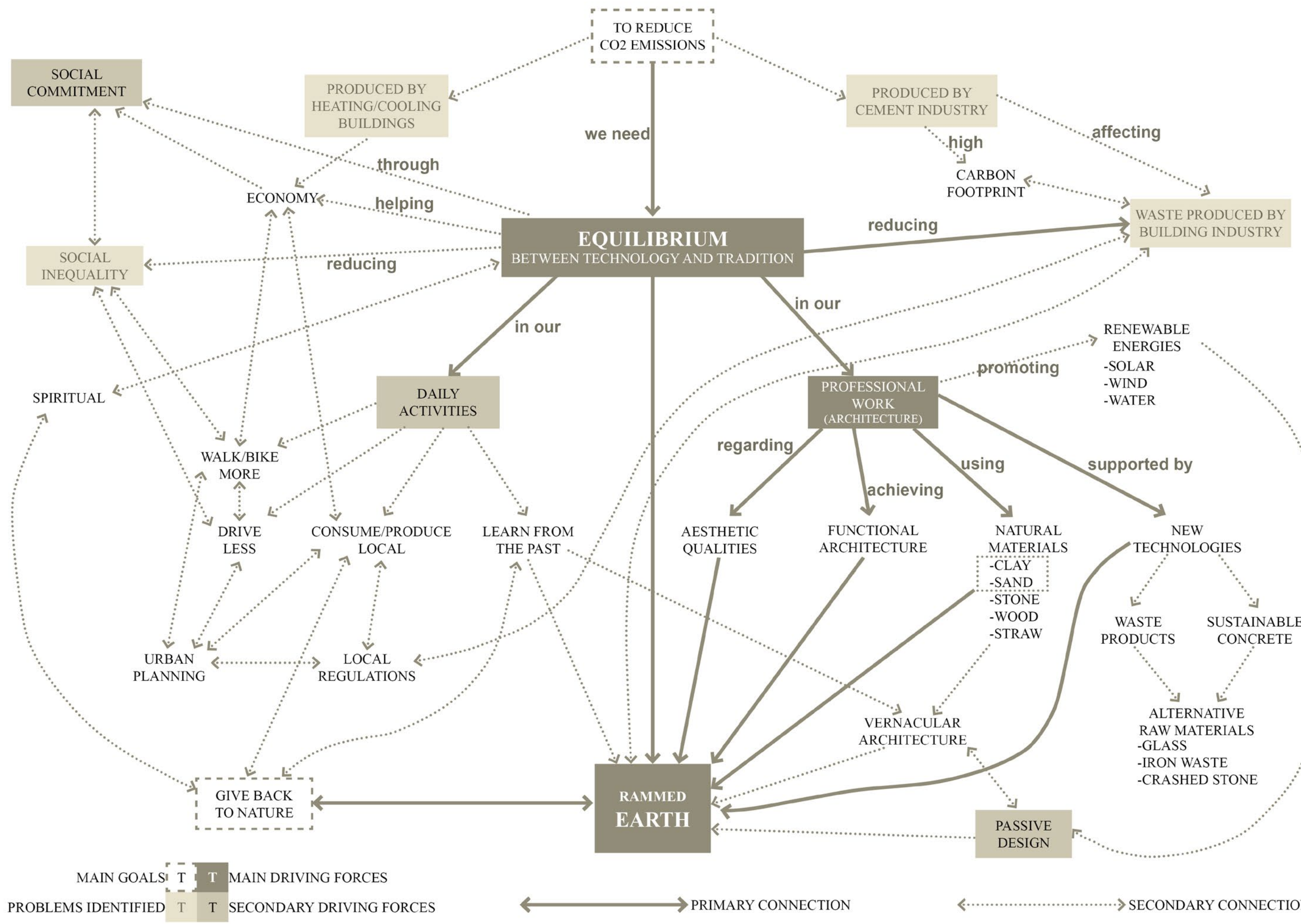
With only 5% of the global $CO_2$ emissions we might think that there are more important problems to solve than the production of cement. But a large part of energy consumption in buildings is related to their materials.

We cannot live like people did in the past, but I would like to see in architecture a balance between technology and vernacular. Can we still achieve regional traditions with the support of global technologies?

## ARCHITECTS ROLE

As architects we have the opportunity to exert influence, until a certain point, in the social behavior. Planners, designers or builders have always guided how persons move, interact and communicate. The responsibility is huge. Reducing $CO_2$ emissions is something we can help with, and how about reducing $CO_2$ emissions produced by the building industry?

Reducing $CO_2$ emissions was another point of departure for the topic of this thesis, the use of earth as building material became a driving force to promote this. In the diagram of the next page, rammed earth is part of a living system that helps to have balance and reduce $CO_2$ emissions with our daily activities.


TO REDUCE CO2 EMISSIONS
we need
PRODUCED BY HEATING/COOLING BUILDINGS
PRODUCED BY CEMENT INDUSTRY
high
CARBON FOOTPRINT
affecting
WASTE PRODUCED BY BUILDING INDUSTRY
SOCIAL COMMITMENT
through
ECONOMY
helping
EQUILIBRIUM
BETWEEN TECHNOLOGY AND TRADITION
reducing
SOCIAL INEQUALITY
reducing
in our
in our
DAILY ACTIVITIES
PROFESSIONAL WORK (ARCHITECTURE)
promoting
RENEWABLE ENERGIES
-SOLAR
-WIND
-WATER
SPIRITUAL
WALK/BIKE MORE
DRIVE LESS
CONSUME/PRODUCE LOCAL
LEARN FROM THE PAST
regarding
achieving
using
supported by
AESTHETIC QUALITIES
FUNCTIONAL ARCHITECTURE
NATURAL MATERIALS
-CLAY
-SAND
-STONE
-WOOD
-STRAW
NEW TECHNOLOGIES
WASTE PRODUCTS
SUSTAINABLE CONCRETE
ALTERNATIVE RAW MATERIALS
-GLASS
-IRON WASTE
-CRASHED STONE
URBAN PLANNING
LOCAL REGULATIONS
VERNACULAR ARCHITECTURE
GIVE BACK TO NATURE
RAMMED EARTH
PASSIVE DESIGN
MAIN GOALS
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SECONDARY DRIVING FORCES
PRIMARY CONNECTION
SECONDARY CONNECTION

My proposal is to embrace alternative technologies in industrialized countries. The building industry has a big responsibility in the way we polute the environment, but in the same way, we as architects have a big obligation to be involved in what the building industry is selling.

Exploring a non-traditional technique like rammed earth in Sweden is a way to develop an alternative building method. Innovation is possible, if we explore; implementation is feasible, if we re-think the way we build today.

# AIMS AND OBJECTIVES

## AIMS

-Explore rammed earth as a system to build in a cold environment like the one found in Sweden.

-Develop a comprehensive guide to produce rammed earth elements in a practical, economically convenient, and why not, fun way in developed countries.

## OBJECTIVES

-Personally the thesis is an opportunity to explore and become an expert in an area that fascinates me, a field that has potential to grow and develop to meet the requirements that architecture demands.

-A different objective is to spread and share the knowledge about building with earth, creating a network of people with similar interests.

# WHY EARTH?

*Universality of earth buildings* (Guillaud, Houben 1994)

Ever since man learnt to build homes and cities around 10,000 years ago, earth has undoubtedly been one of the most widely-used construction materials in the world. (Guillaud, Houben 1994). In the illustration above, regions in the world with earth as building tradition. (Guillaud, Houben 1994)

Even today, one third of the human population resides in earthen houses (Minke 2009). We can identify numerous methods when building with earth, like adobe, cob, straw-bale or rammed earth.

Different techniques of building with earth will be described later in this report. But, important to mention, this thesis will focus only in rammed earth.

There is a global increase in the demand of low-cost and sustainable constructions, therefore it is important to consider the viability of rammed earth in a non-traditional climate region like in Sweden.

Talking about Sweden, there is a lack of knowledge and guidelines when building with rammed earth.

look
**under your feet**
and build
(Hassan Fathy)

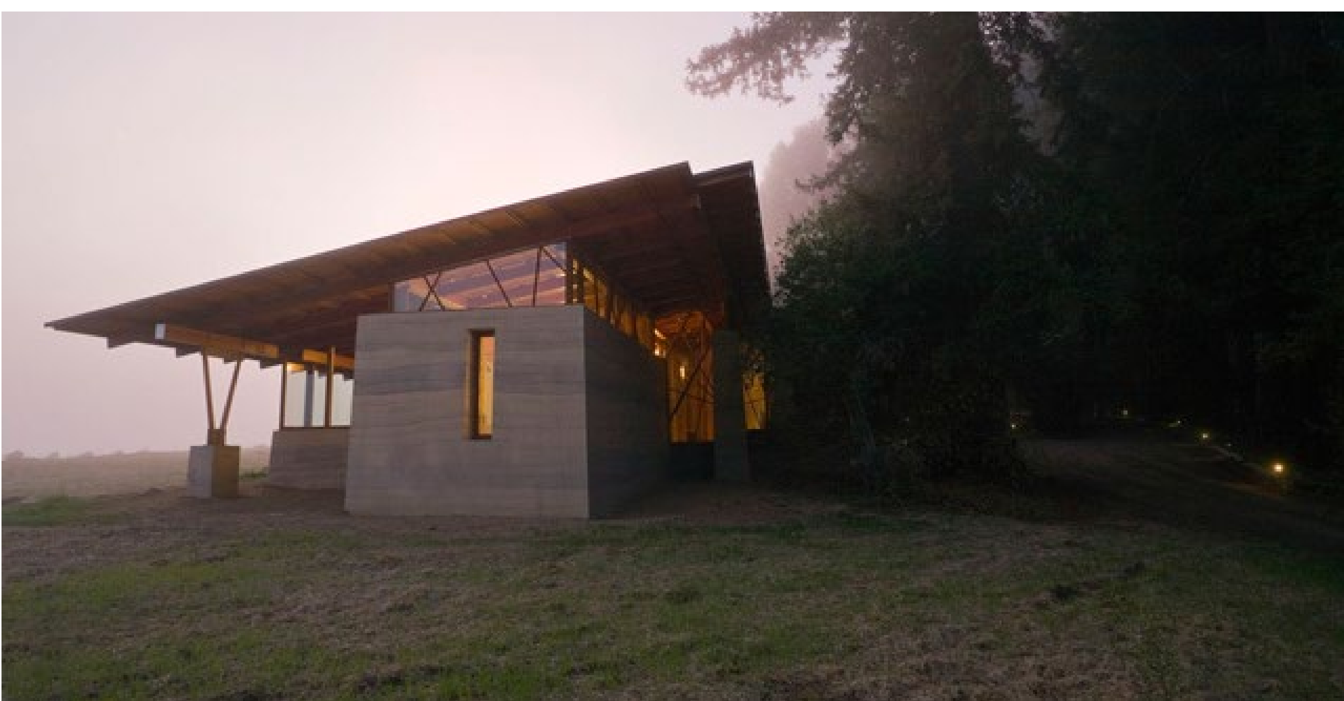
Soil is not a problem, according to SGI (Swedish Geotechnical Institute) illite is the dominating clay mineral in Sweden. Clays that do not shrink and swell extensively, such as kaolinite and illite, are excelent for rammed earth walls (Easton 2007). This is explained in page 51.

It is true that for each project specific tests should be carried out; but generally speaking, to build with rammed earth in Sweden is feasible, and the material is easy to obtain.

It is possible that people in Sweden, like in Mexico, do not know that they could build with the material under their feet. Builders or developers transport earth from building excavations far away without giving it any use. In many cases that earth is appropriate to build.

There are good examples of earth-technologies in cold regions like in Canada; here, rammed earth is widely known and used for more than 20 years (see page 94).

Bodega Residence
Cutler Anderson
Architects
(© 2013 Cutler
Anderson Architects)



In Germany, Austria and France rammed earth is popular and is supported by standard guidelines and regulations. In these countries (like in Sweden) labor cost is expensive and rammed earth houses might seem luxurious now, but investments in this area create a network of collaboration with third world countries, where labor cost is cheap and people is eager to "learn" what industrialized countries are doing.

Anna Heringer from Germany, in Bangladesh; Martin Rauch from Austria, in Africa; or Gernot Minke from Germany, in Latin America are different names of people sharing knowledge in developing countries. Can Sweden be an inspiration for developing countries?

Combining clay construction in a modern multi-level building with an absolute minimum of cement serves as an example of extraordinary importance extending far beyond the immediate region. (Kapfinger, Singer 2010)

Handmade School
Anna Heringer
Bangladesh
(© 2012 Vaumm)

# DELIMITATION AREA

There are different methods to build with earth; like mentioned before, techniques like adobe, cob or straw-bale will not be investigated. The intention of this work is to analyze the viability of rammed earth in a cold climate.

Rammed earth applications are vast. It is used in walls and floors, from residential purposes to urban features, like Quentin Branch is doing in the United States with rammed earth walls for sound insulation. Rammed earth is worldwide used in:
-Houses
-Commercial buildings
-Office buildings
-Urban spaces

Nevertheless, the focus of this work will be in the production of earth walls. The time-factor is crucial to center the attention in how to build walls, in Sweden aspects like weather conditions, building traditions and economy need to be analyzed and comprehended.

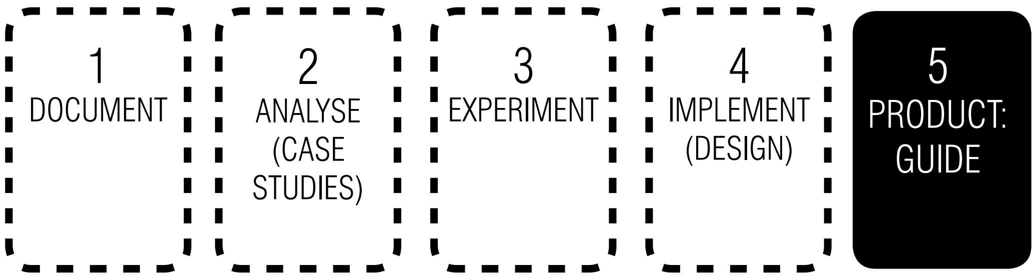
There are tacit problems that this work intends to describe in our local context:

-A mind set, people believe that earth is not safe, in comparison with wood, concrete or bricks.

-People may not be aware that it is possible to build with earth.

-In the building sector, there is a lack of knowledge and standard guidelines when talking about building with earth.

-Earth constructions are easily related to do-it-your-self alternatives when material or economic resources are scarce.




# METHODS

-Documentation: literature, study visits, workshops.

-Analysis: general and special characteristics of rammed earth, compared to commonly used materials like concrete or wood.

-Case studies: analyze built projects that serve as references to implement rammed earth in Sweden.

-Experiments: explore the material through products like benches or planters. Exploring with earth consists in applying the material to local conditions, analyzing workability, costs, strengths and weaknesses.

-Implementation: design an office building, introducing rammed earth features into a urban context.

(part 1)

# EARTH AS BUILDING MATERIAL

# DIVERSITY OF EARTH

We can identify multiple building methods in the tradition of earth construction, with innumerable varieties reflecting the identity of each location and culture.

Personally, the heavy expression of a finished rammed earth wall still impress me. But one could choose a technique that adapts to the local situation. I will briefly describe seven techniques, the most common ones.

**rammed earth** - on all five continents, rammed earth has been well-known for centuries as a traditional wall construction technique (Minke 2009).

A rammed earth construction demands an intense labour work, but the reward is priceless: the natural colors of the different layers and the powerful architectonic expression are qualitites that architects uncover with this techique.

In rammed earth soil is compacted in a formwork. This technique allows to build monolithic walls.

Rammed earth wall (© 2012 jones studio inc)

Adobe bricks
(© Architects Rudank-
o+kankkunen LTD)

**adobe** - blocks of earth produced manually by throwing wet earth into a formwork are called adobes (Minke 2009).

Adobes are also called mud bricks or sun-dried earth blocks. Adobes are produced by filling moulds, typically of wood, with a pasty loam mixture, or simply throwing by hand the loam into the moulds.

The dimensions of mud bricks varies a lot but a common size is 40 x 40 x 8 cm height.

**compressed earth blocks** - manual production of earth blocks by compressing them in wooden or steel moulds. Nowadays the process is mechanized.

Compressed earth
blocks
(Sobajima 2011)

**cob** - the cob method consists of stacking earth balls on top of each other and lightly tamping them with the hands or feet, to form monolithic walls.

The surface in a cob wall is sliced after tamped to procure an even finish.

Cob construction
(© AbeySmallcombe)

**straw-clay** - in this technique the soil used is very clayey and is dispersed in water, then is added to the straw. The function of the clay is to act as a binder for the straw.

**direct shaping** - this technique makes use of a plastic earth and makes it possible to model forms directly without using any kind of mould.

Moist loam has the possibility to be shaped better than any other building material. The practice is widespread in Africa and Asia, but is also known in America and Europe. Direct shaping is probably the most primitive technique since no tools are required to manipulate earth.

**wattle and daub** - a bearing structure is filled with a net from vegetable matter. An extremely clayey earth is mixed with straw or other sort of vegetable fibre to prevent shrinkage, the earth is thrown and shaped into the structure with the hands.

Plastic loam has been used for thousands of years to fill gaps in long houses where the logs are laid horizontally and in palisades (Minke 2009).

This type of technique have been used in tropical, sub-tropical and moderate climates of the world. It is believed that the method is even older than rammed earth and earth block works.

Wattle and daub is also known as thrown loam or wet loam infill in skeleto structures.

(part 2)

# RAMMED EARTH

# HISTORY

Earth construction techniques have been known for over 9000 years (Minke 2009). In the city of Jericho, Palestine, we find one of the first examples of mud bricks, believed to be created around the year 7500 BC.

All over the world we can find examples of earth constructions, from the Great Wall of China to the Pyramids in Teotihuacan, Mexico, rammed earth was used as a building technique, and it was later covered with stones.

It is hard to identify when and where was rammed earth used for the first time. It is believed that all the great civilizations in the past used rammed earth, not only for housing but for temples and monuments as well.

Excavations in China have uncovered rammed earth constructions dating from the seventh century B.C. (Easton 2007). All over the world we appreciate rammed earth structures, some of them are still used, but why don´t we build with this material anymore?



Earth architecture is not exclusive for warm climates. We have evidence of rammed earth buildings in Europe, most probably introduced by the Romans and Phoenicians.

Rammed earth has been used worldwide for thousands of years. The knowledge was transmited from one generation to the next one. But in one point of our history this transfer of information was interrupted.

One of the most enthusiastic promoters of rammed earth was Francoix Cointeraux, who saw it was a way of providig cheap, healthy and durable housing (Guillard, Houbert 1994). His writings from the eighteen century were translated into various languages.

During the eighteenth century, Francois Cointeraux discovered pisé de terre in the region of Lyon. He believed pisé was a way in which man could improve the quality of his life.

A view of the towers of La Alhambra, in Spain, built around 1348

La Alhambra is a UNESCO World Heritage Site. Some parts of the complex, like these 45 m height towers, were built with rammed earth. When the Moors invaded Spain in the eighth century they brought with them the techniques of both rammed earth and mud brick construction. (Easton 2007).

(©2007-11 Trek Exchange LLC)

*Pisé de terre* is the french term for rammed earth, name that is frequently refered in books and literature. The Spanish name for this technique is *barro apisonado* or *muro de tapial*. The word *muro* is wall, the word *tapial* is pre-roman and is a voice of onomatopoeic origin: “tap” intends to reproduce the sound made when earth was rammed (wikipedia.org).

Cointeraux founded a school in Paris in 1788 for the study of rural architecture, with his personal mission to spread the knowledge of pisé. In 1790 and 1791 he published four texts about tools, soil, formwork, and methods for building with pisé.

The idea of building with rammed earth was then spread to Great Britain, architects like Henry Holland produced small modifcations to the techniques described by Cointeraux. The word arrived to other countries in Europe and to America.

We can say that an uprising demand in buildings with rammed earth was originated by Cointeraux´s writings in 1780. But his work started to fall down in the 1850s with the introduction of new materials like fired bricks.

A course organized by Alfred Engelhardt, mans in suit and tie serve as propaganda to learn how to build with rammed earth (Fisabre, Wilson 2012)

These new materials were not as economic as free earth, but improved methods in production and development in railroads, made manufactured materials accessible and reliable. The new materials were easy to work with and represented the image of a wealthy and modern country.

Earth was labeled as a material for the poor, and it was mainly used in farms, but probably not considered for industrialized cities.

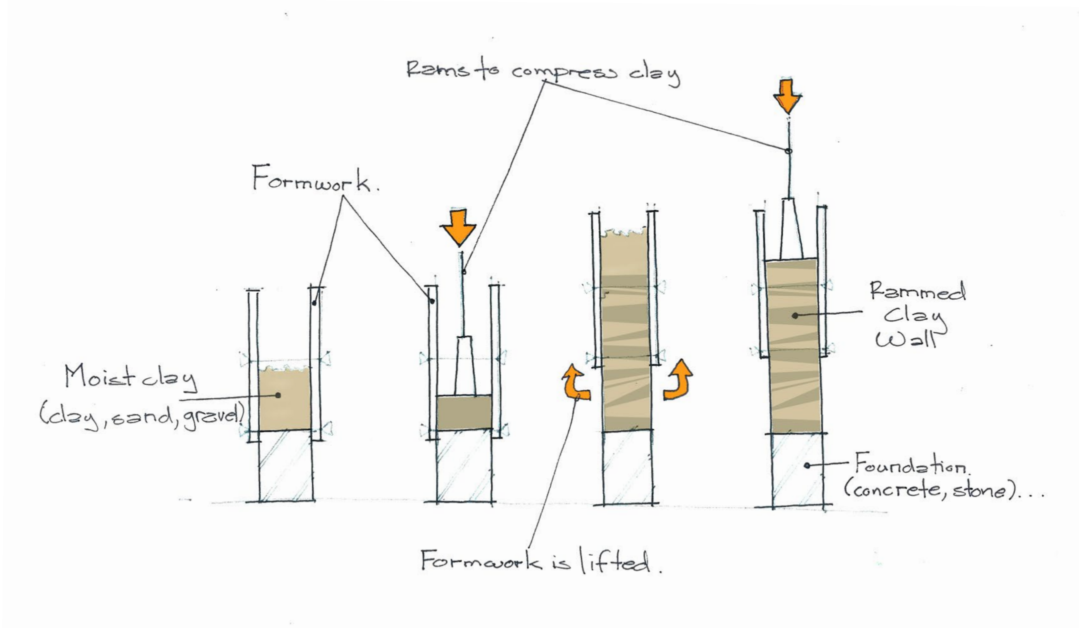
*Alfred Engelhardt, in his book of earth building in 1919, objects to the prejudiced view of earth as the “way of building for the poor” and oposes historical examples of “earth houses, not stables, not miserable huts, but beautiful, stately one or more-storey houses in the city or in the countryside”.* (Fissabre, Wilson 2012)

The Great Depression and shortage in housing caused by the World War I brought a new wave in the demand of earth constructions. It is believed that this re-assessment of earth as building material was stronger than Cointeraux´s work to promote pisé. The information available helped people to build their own low-cost houses.

Nowadays we are experiencing a third wave in the demand of ecological and natural constructions, due to the environmental and economic issues that the building sector faces today. When we talk about rammed earth, Australia is leading the mass production of stabilized pisé, followed by the United States and Canada.

France, Germany and Austria have a strong tradition in rammed earth without the use of cement as stabilizer. CRATerre is probably the institution leading education and training in earth construction. In Germany the German Association for Building with Earth (DVL) organizes workshops and conferences of building with earth.

Rammed earth house in Harplinge, Halland (Jordhusbygge 1950)




# HOW IS RAMMED EARTH PRODUCED?

Rammed earth is a massive and monolithic form of earth construction (Röhlen, Ziegert 2011). It is a building method in which a mixture of clay, sand and gravel is poured into a formwork to be compacted.

In the sketch above, the basic technique of ramming earth into a formwork, producing monolithic elements . There are different types of forms, wooden formworks are the most used, they can be lifted when a section has been rammed. There are metal formworks, used in bigger projects, similar to those utilized for concrete works.

The beauty of a rammed earth wall lies not only in its architectural qualities, but also in the way it is produced, assesing local handcrafts that are almost forgotten in the building environment. In addition to this the material (clay, sand, gravel) can be reclaimed by nature when a building reaches the end of its life-cycle.

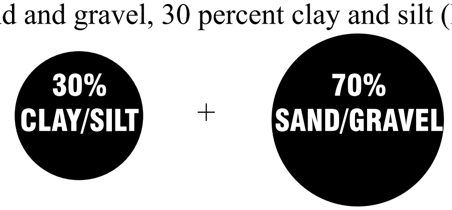
# BUILDING PROCESS

## 1. PREPARE THE SITE

Once the project is defined and we are allowed to build, we need to clear the site like in any other building method. We need to free the space from unwanted vegetation and confine an area where we can store tools and material to build.

## 2. GET THE SOIL COMPOSITION

Preparing the adequate earth mixture can be complicated, roughly 70 percent sand and gravel, 30 percent clay and silt (Easton 2007)




It is possible to find this mixture as natural composition in soils. But in case we need to import clay or aggregates, is reasonable to buy them. In Sweden the company Bara Mineraler sells bags of clay up to 20 kg. Once we have the correct mixture of earth in the site, it would be wise to protect it from rain.

## 3. WET THE MIXTURE

The soil needs to be wetted, but not abundantly. If we take a handful of the mixture and press it, this should not fall appart, but neither stick to the fingers, it should be almost dry and break if you throw it from a height of one meter. To wet the material is recommended to spray it, the water content should be between 8-10% in the mixture.

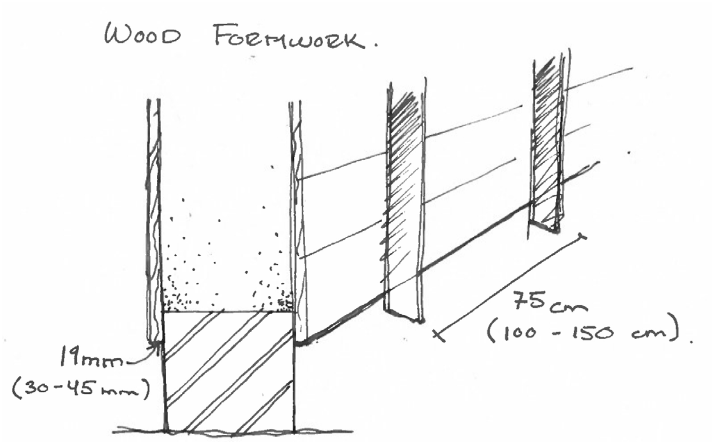
## 4. FOUNDATIONS

The foundations for a rammed earth wall are like the ones used for a heavy masonry wall such as bricks or concrete. In Sweden foundations of stone, concrete and leca-blocks have been used in different rammed earth projects.

## 5. BUILD THE FORMWORK

Formwork is a big component in rammed earth buildings, like it is in concrete works. In most of the cases to settle the formwork takes more time than filling and ramming the earth. In the traditional method the formwork consists of two modules of wood that could be carried by two persons and moved to the next level.

For a typical construction, wood of 19 mm thickness with vertical reinforcements every 75 cm is recommended. Usually a wood module that could easily be lifted is 70 or 80 cm height with variable lengths.



Nowadays complex systems to reduce time and costs are implemented with wood and metal formworks. These formworks are similar to those used in concrete works.


Rammed Earth Formwork (© 2012 RammedEarth Builders.com)

## 6. POUR AND COMPACT THE EARTH

With rammed earth techniques, moist earth is poured into a formwork in layers between 12 and 15 cm thick, and then compacted by ramming (Minke 2009).

WHEN POURING

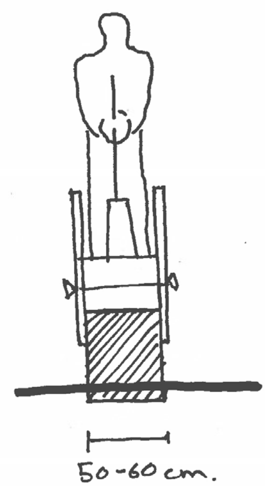
**15 cm HEIGHT LAYER**

→

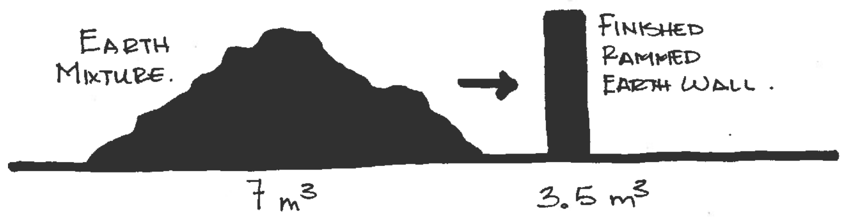
AFTER COMPACTING

**7 cm HEIGHT LAYER**

The higher the formwork, the more difficult is to maneuver and compress the mixture. In walls of 50 to 60 cm thick the space is enough for one person to work without complications, but if the wall section is slimmer the process would be different and smaller tools might be required. In the past, earth was rammed using conical or flat rams. Today, pneumatic rams are recommended for more efficient work.



To calculate the quantity of earth needed to build one must know that the volume of mixture is usually around 50% more than the volume of a built element. In other words, if the volume of the finished walls of a building  is 50 cubic meters, we will need around 100 cubic meters of earth mixture.




The formwork can be removed after compactation, allowing walls to breathe and dry in a satisfactory period of time, only a few days after (see Drying Period in part 4, Technical Characteristics).

During construction, rammed earth elements are usually exposed to rain and they are sensitive to erosion, it is important to protect them in every step of the building process.

## 7. PREFABRICATION

Rammed earth structures can be load bearing, with a density of two tons per cubic meter, wall elements are good for sound insulation and thermal mass.

The possibility to create prefabricated elements of rammed earth could facilitate to build almost all year long, instead of a few months during the summer that the traditional technique allows.

A limitation due to the density of the material (see page 66), is that prefabrication would be assisted almost all time by cranes or mechanized processes.

# 8. TOOLS AND EQUIPMENT

These are the tools we used in a rammed earth workshop I attended last April in Norfolks, UK. (see appendix A)

Normal concrete mixer. (David Martínez Escobar 2013)

Metal ramer, nowadays pneumatic ramers are used for larger projects (David Martínez Escobar 2013)

# RAMMED EARTH IN A WARM CLIMATE

In regions where days are warm and nights are cold, and where average temperatures lie between $15^0$ C and $30^0$ C, the heat capacity of a material is very important to create a comfort indooor space.

Rammed earth has a high heat capacity (see part 4, Technical Characteristics). The material can store heat during the day and release it during the night, this means that the material will delay the outside temperatures for reaching the indoor space.

Nevertheless, there is a wrong belief that rammed earth works better in warm climates than in cold climates. In extreme warm weathers, to reduce heat gains, rammed earth have been installed using insulation on the exterior, afterwards covered with stucco or clay plaster.

# RAMMED EARTH IN A COLD CLIMATE

Rammed earth walls have been built on six continents in all climates, from the equatorial tropics to the coldest northern latitudes (Easton 2007).

Sweden has a strong tradition of building with earth. Methods like straw-bale or wattle and daub are widely used; clay plasters are frequently applied as the final layer in these techniques. Rammed earth might not be that common, but still, there is evidence of rammed earth buildings in Sweden, some of them built in the 1940s.

Rammed earth house in Harplinge, Halland. (Correia, Merten 2011)

The picture below shows a 400 $m^2$ rammed earth house in Harplinge, Halland. Annika Ekblom in her thesis work *Om Hus av Jord och Lerhalm*, mentions that the house was built in 1948 by Georg Norrgren, with 30 cm thick earth walls.

Dir. Georg Norrgrens rammed earth house in Harplinge, Halland (Jordhusbygge 1950)

One obstacle of rammed earth in a cold climate is insulation. A rammed earth wall of 50 cm thick in a cold climate will have a U-value of 2.0 $W/m^2K$ (Minke 2009). European standards aim for a U-value of 0.30 $W/m^2K$ in materials.

This means that if we would like to build with rammed earth according to norms in Sweden, we would have to insulate the walls. Nevertheless, even today, houses in Halland are built with non-insulated rammed earth walls.

An interesting approach for rammed earth in a cold climate is the use of passive design. Since rammed earth has a high heat capacity, the building´s thermal mass can store solar heat by being exposed to direct sun during the winter. During the summer  it is recommended to protect the wall from direct sunlight exposure.

# EXPERTS IN SWEDEN

## HANS BALTHIUS - BUILDER

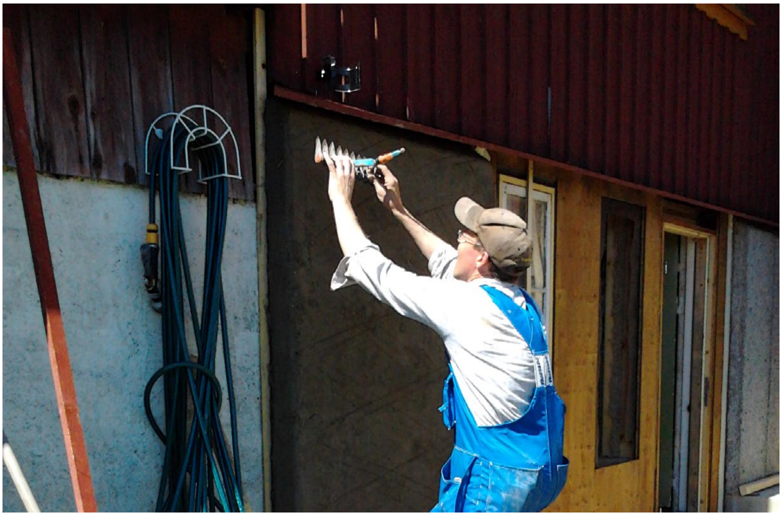
Expert in rammed earth construction, Hans was the responsible of building the houses in Steninge, he now lives in Gotland.

On September, I had the opportunity to meet Hans Balthius at Halland, where he showed me one of the projects he built with rammed earth. It was inspiring to talk with Hans, beeing one of the few persons building with this technique in Sweden.

## ULF HENNINGSSON - BUILDER

Expert in building with natural materials in Sweden. Ulf arrange and participates in diverse workshops about building with natural materials all year round.

I participated in a workshop about building with strawbale at Nääs this summer, Ulf was collaborating as a teacher, together with other two people, this workshop is held once a year at Nääs.



In the photo, Ulf Heningsson working with a clay plaster during summer 2012. (David Martínez Escobar 2012)

## LARS-ALLAN PALMGREN - ARCHITECT

Lars-Allan Palmgren has years of experience in education and practice. His licentiate exam was called “Swedish Earth Buildings with Clay or Lime 1750-1950”

I met Lars last year in the LEHM International Conference of Building with Earth (see appendix B). Lars has his own consultant company in Stockholm, La Parc AB.

In the photos, clay house in Sweden. (Palmgren 2001)

# WEATHER RESISTANCE

Although there is evidence of rammed earth structures that have been exposed to weather conditions for long periods; in central and northern Europe, different considerations need to be implemented to avoid damages in the walls due to heavy rains or frost.

Rammed earth is not moisture or frost proof and the resistance of rammed earth to the effects of moisture varies considerably. (Röhlen, Ziegert 2011)

## STABILIZATION

Stabilization is defined as the abscence of change, the creation of a steady physical state. Within the context of rammed earth construction, stabilization is the elimination of the change in volume that occurs in a soil as it absorbs and discharges water. (Easton 2007)

Stabilization has been present since the beginning of earth buildings history. In Babylon, bitumen was used to stabilize mud bricks, lime has served as stabilizer for the moor and chinese civilizations, among others. Today, cement is the most used stabilizer.

Stabilization has been present in earth construction among different civilizations, if we think again about La Ahlambra, in Spain, we find two main rammed earth techniques.

In the study *Technology of Rammed-Earth Constructions ("Tapial") in Andalusia (Spain): Their Restoration and Conservation*, Eduardo Sebastián and Giusepe Cultrone explain that there were two main methods of rammed earth used in La Alhambra:

A) Tapial Real: consisted of a series of layers from 2 - 5 cm thick, going to 8-12 cm and 60 - 80 cm thick. The finish on the walls was applied once the formwork had been removed.

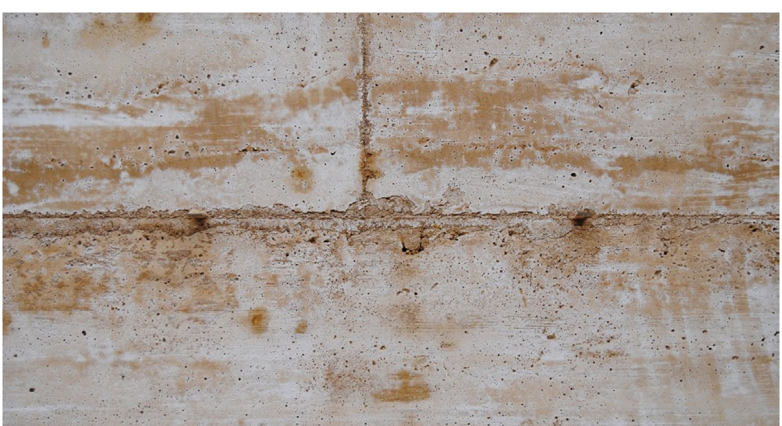
B) Tapial Calicostrado: this technique appeared as a solution to the damage caused by erosion when rammed earth wall was exposed to rain water. A "strip" of mortar with a high proportion of lime was applied to the outside and the earth was then trodded down so that the lime mortar became embedded in the wall, forming one single structure.

The Justice Gate
La Ahlambra, Spain
(Casado 2010)

The *Colicostrado* is a technique in which a material protects rammed earth from erosion. This material is poured in the same formwork, and becomes part of the wall. Photo (1) shows a wall from Castillo de Gontar, Spain, using the *Colicostrado* technique, easy to see the light color of the lime mortar.

1. Tapial Calicostrado (Quesada Arquitectos Asoc 2004)

Photo (2) shows a new rammed earth wall in Spain, using cement instead of lime mortar, but the concept remains the same. When we see these pictures, it is impossible not to think about Martin Rauch´s house, with clay bricks used to slow down erosion in the exterior walls (see page 164).



2. New rammed earth wall in Spain (Castellarnau 2012)

There is a general belief that earth buildings are not weather resistant, but under ideal conditions soil can be stable simply through compactation. The ideal soil is the one in which the clay minerals are activated to create a natural cementation.

David Easton in his book *The Rammed Earth House* mentions that stabilization does not necessarily require the addition of cement to the soil (Easton 2007, p.108). Gernot Minke in his book *Building with Earth*, explains that in general, it is unnecessary to raise the water resistance of building elements made from earth (Minke 2009, p.40).

In every case, the architectural design should be as carefully planned as the building process. Earth walls should be sheltered by overhanging roofs or shingles, as well as against rising humidity from the soil through the foundation.

Another way to improve the erosion resistance of elements is through the insertion of brick strips or tiles that can be rammed together with the mixture, like in Rauch´s House (see page 164).

In Sweden, there are good examples of buildings that do not use stabilizer. In the autumn of 2012 I went to Halland, to visit a Cob construction made by Hans Balthius, the building consisted of a small experimental house using clay from the site.

In the pictures in next page we can appreciate the damage caused by rain. During one year Hans let the clay plaster exposed without any covering layer.

The picture above shows a part of the house that has no overhanging roof, causing considerable damage in the wall. The picture to the bottom is the part of the house with an overhanging roof of water reeds, that protects the clay plaster, no visible damage is caused after one year of exposed and un-treated clay plaster.

Hans Balthius´ Cob house in Halland, Sweden.
Overhanging roof protecting the clay plaster.
(David Martínez Escobar 2012)

## HAKKA HOUSES - FUJIAN, CHINA
Building period, 1790

Archaeological research has revealed that there have been communal houses built of rammed earth in China, Central Asia, and East Asia since the Neolithic period 6,000 years ago. (whc.unesco.org, 2012)

In the region of Fujian, houses are formed compacting earth, mixed with stone, bamboo, wood and other available materials. The bamboo in the walls function as reinforcement, producing earthquake-proof buildings that are warm in winter and cool in summer.

There are three basic types of dwellings: the round dwelling, the rectangular and one last called the Phoenix dwelling. The rectangular and circular ones consist of three to five floors, with the kitchen in the ground floor, food storage in the second (keeping the grain dry with the heating from the floor beneath) and rooms on the top floors.

*A woman carries baskets full of goods across a river near a cluster of traditional Hakka Tulou homes in the county of Yongding, China*
(Pyle 2009)

These historical buildings have withstood several strong earthquakes in recent centuries. (Minke 2009, p.135) In the round dwelllings the walls were built inclined towards the centre, enhancing the natural force of gravity to hold the building together. The dimensions of a wall is as thick as 1.8 m in the ground level and decreases with height,  reaching an alltitude up to six floors.

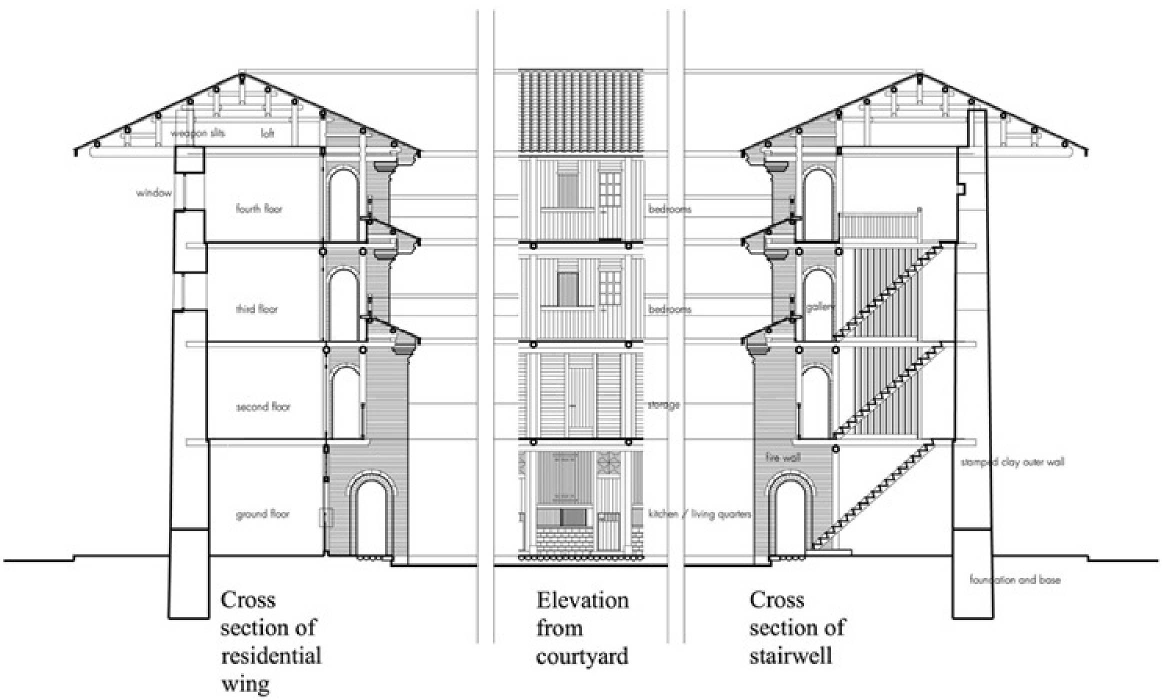
The largest diameter of a circular house is of 82m, it is believed that it could house 80 families, around 600 people. Many of these houses served as fortifications in the past, with small windows and only one entrance to the house, the dwellings were impenetrable.

The so called Phoenix dwellings follow the principles of Confucian order. The typology of the building was 58m width and 108m depth, with the entrance facing south. Through this entrance one access the center with high ceilings, that serves as main hall for worship.

*Tourists visit Tulous in Yongding, Fujian*
(Xinhua 2012)

According to the Swedish Meteorological and Hydrological Institute, annual precipitations in Göteborg are estimated to be from 1,200 to 1,400 milimiters. But in Fujian, average annual precipitation is 1,400 – 2,000 millimetres. (wikipedia.org) How is it possible that these enormous structures are today standing still?

The Hakka Houses do not use the *Colicostrado* method in the rammed earth walls, like in La Alhambra, but over-hanging roofs have protected the houses from direct rain. The houses have been exposed to erosion for a long period and they are still used. Lime was used in the construction as stabilizer.




Hakka houses
*Section and Courtyard Elevation*
(Aaberg-Jørgensen, ca 2000)

# RAMMED EARTH TODAY

There is an increase in the demand of building techniques like rammed earth. Architects and builders are often attracted by the natural appearance of the material, taking advantage of its physical characteristics to design and ecologically friendly buildings.

In the US, Australia, France, Germany and Austria, rammed earth is produced following standard guidelines similar to concrete. But in many countries is still considered to be a “do-it-your-self” technique.

People tend to relate earth buildings with hand-made constructions, exclusive to the countryside. Its reputation is often an alternative to social developments when other resources are scarce. Today, rammed earth is produced using mechanized processes, meeting architectural qualities and requirements like any other building material. The study cases described in the end of the report will help us to understand how rammed earth is being used today.

House Rauch
(Bühler, Rauch 2008)

(part 3)

# SOIL PROPERTIES

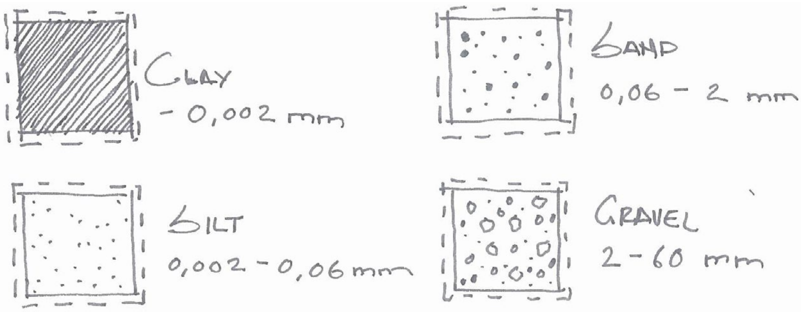
# PARTICLES´ SIZE

When we build with earth, soil is classified by the size of its particles. In general, there are five basic soil types: gravel, sand, silt, clay, and organic soil.

Particles with diameters smaller than 0.002 mm are termed clay, those between 0.002 and 0.06 mm are called silt, and those between 0.06 and 2 mm are called sand. Particles of larger diameter are termed gravels and stones. (Minke 2009)

In order to prepare and manufacture a material for a building purpose we need to understand the raw materials of which it is made. When we talk about earth building materials, we need to understand the binding agent: clay.

Like in concrete used for construction, earth building materials consist of a binding agent and aggregates. We can say that a binding agent like clay functions as the glue, and aggregates like sand and gravel function as the skeleton, which gives strength and rigidity to the body. Clay, sand and gravel combined with adequate proportions create a suitable earth material to build.




# DIFFERENT SOILS

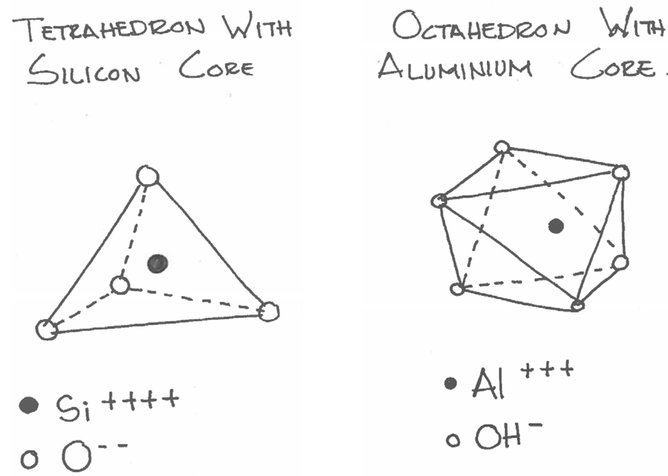
Clay, as the binding agent in earth, occurs in different forms with widely varying properties. Soils where the clay fraction is less than that of the granular constituents are known as earth.

Mixtures with high binding characteristics are known as rich mixtures, and those that are not very cohesive are known as lean mixtures.

# CLAY MINERALS

Clay minerals occur in nature in different forms, according to local characteristics of the soil. Clay minerals are silicates with a lamellar structure with a size ranging from ca. 0.1 to 4 micrometer (um). (Röhlen, Ziegert 2011)

Depending on the kind of clay minerals, they can be grouped in two or three layers of minerals. These so-called two or three layer clay minerals have different structures, tetrahedral or octahedral structures.



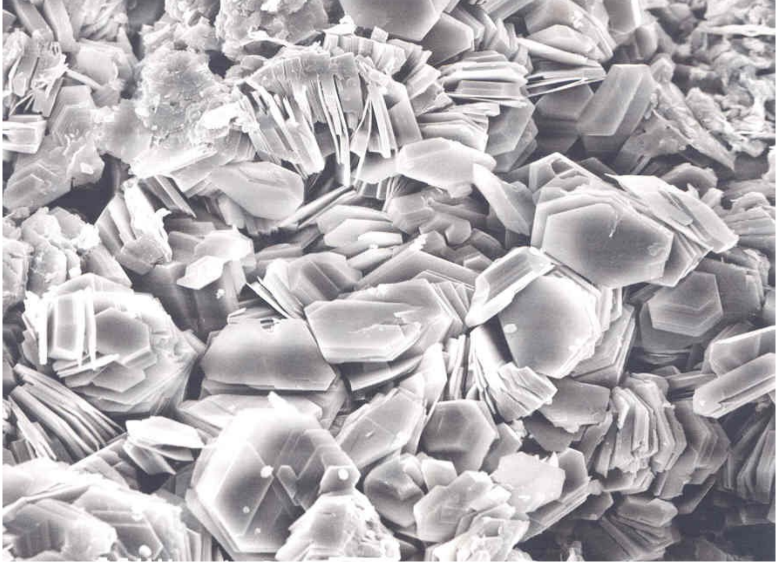

*The binding force of the clay minerals can be attributed to localised differences in charges that occur at the surfaces of the sheets. In contrast to other binding agents used in construction, where hardening is a product of chemical cure, the cohesive effect of clay minerals derives from the physical attraction of the particles.* (Röhlen, Ziegert 2011)

This means that the particles react with the water molecules. The binding force decreases as more water molecules are bound between and within the structure of the clay minerals. When the water molecules are not present, the binding force becomes stronger.

The colors of different clays is caused by the presence of metal oxides and hydroxides, like iron, manganese or aluminium. But the color is not an indicator that clay is adequate for building purposes or not.

### TWO LAYER CLAY MINERALS

The group of two layer clay minerals is known as *kaolinite* group.



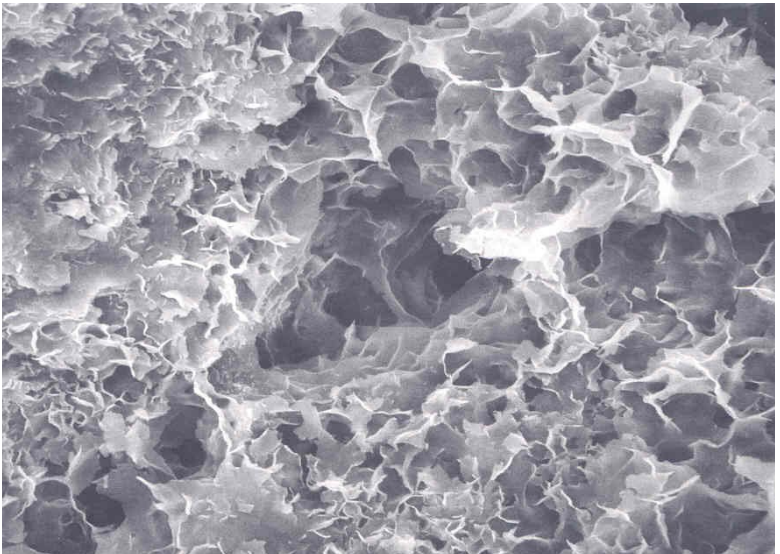
Electroscan Microscope Image of Kaolinite Clay (© 2004 Petro Tech Associates)

Kaolinites are weak as binding agent compared to three layer clay minerals, but this does not mean that they cannot be used in rammed earth.

## THREE LAYER CLAY MINERALS

The group of three layer clay minerals consist of an octahedral sheet sandwiched between two tetrahedral sheets. The most important group of three layer clay minerals are micaceus minerals, of which the most common is *illite*.

According to different sources, the binding force of the three layer clay minerals is higher than of the two layer clay minerals. To produce rammed earth and according to SGI (Swedish Geotechnical Institute) illite is the dominating clay mineral in Sweden.



Electroscan Microscope Image of Illite Clay (© 2004 Petro Tech Associates)

# SOIL IDENTIFICATION

In earth building techniques it is important to measure the proportions of clay and sand in the loam, but is also important to have the appropriate clay minerals. Due to the difference in binding force between one type of mineral and the other, some clay minerals may not have adequate cohesive properties.

It is imperative in the planning process of every project to identify which type of soil exist in the site. If the soil counts with a large amount of clay particles, the addition of imported aggregates would be necessary.

Informal experiments can help us to have an estimation of the clay and sand content in a mixture. But in order to demonstrate which type of mineral is present, we would have to count with the support of a geotechnical laboratory. This is a complication when we talk about earth building materials, since these tests can make the process to build slower and in some cases expensive.

Experience in the field might be enough to identify the soil for a small project, but for larger projects the support of a geotechnical laboratory is mandatory.

# SOIL TESTING ON SITE

In the next pages two samples of soil are compared to document the analysis of earth as building material.

The samples are shown in the pictures at the bottom of this page. The picture to the left shows earth from a building site in Johanneberg, near Chalmers, it is a sandy mixture. The picture to the right shows a sample from the area of Sjövik, Lerums Kommun, a clayey mixture.

As we can easily appreciate in the photos, the earth from Sjövik (right) has less quantity of aggregates like sand and gravel particles. We can do this by sieving the earth with a 1mm metal siever.

Another thing was easy to notice at the moment we took the samples: its natural clay-consistency. The sample from Sjövik, with its natural moisture content was very clayey, almost like a gum; in comparison with the sample from Gothenburg, that felt very sandy and did not sticked to the fingers.

It was not enough, with this basic sieving, to see if these earth mixtures were appropriate to ram. At this level, we cannot differentiate the quantity of fine particles of sand, clay and silt.

Left, Gothenburg soil sample; right, Sjövik soil sample. (David Martínez Escobar 2012)

## JAR TEST

In this test two cups of earth were poured into a glass jar, which then was filled with water, shaked and let to rest for a couple of hours. The heavy particles like little stones and sand settled first in the bottom.

Generally speaking, if the layer of fine material on top is one-half to one-quarter as thick as the sand and gravel layer in the bottom, then the soil has some promise for use in a wall building. (Easton 2007)

Jar Test with the earth sample we took from Göteborg. The fine particles are less than a half of the larger particles. (David Martínez Escobar 2013)

Observations in the jar test:

| | GOTHENBURG SAMPLE | SJÖVIK SAMPLE |
|---|---|---|
| Clay-silt | 20-30% | 50% |
| Sand-gravel | 70-80% | 50% |
| Smell | NO | NO |

## SMELL TEST

Usually mineral soil that is suitable for building has no smell, if we perceive a strong smell in the mixture, we could be talking of organic soil, and can be discarded for material to build.

Ball Dropping Test. (David Martínez Escobar 2013)

## BALL DROPPING TEST

The mixture to be tested should be a natural moist sample. Forming a ball of 4 cm in diameter, the ball should be able to shape but not stick to your fingers. If we let the ball fall from 2m height different results may happen.

If the ball disintegrate it has a poor clay content and is not suitable to build, if the ball shows no cracks at all but just squash, this has a high clay content and the addition of aggregates should be contemplated. If the ball break appart but do not desintegrate it is a semi-rich earth and is suitable to use in rammed earth works or compressed blocks.

In our tests, the ball of soil from Gothenburg showed some cracks, but did not desintegrate, which means that this soil, generally speaking, can be used to build with rammed earth.

The ball of soil from Sjövik just squashed, which means that the clay content is to high to ram. We made four different tries with the same soil, but the results were almost the same.

# SOIL TESTING IN LABORATORY

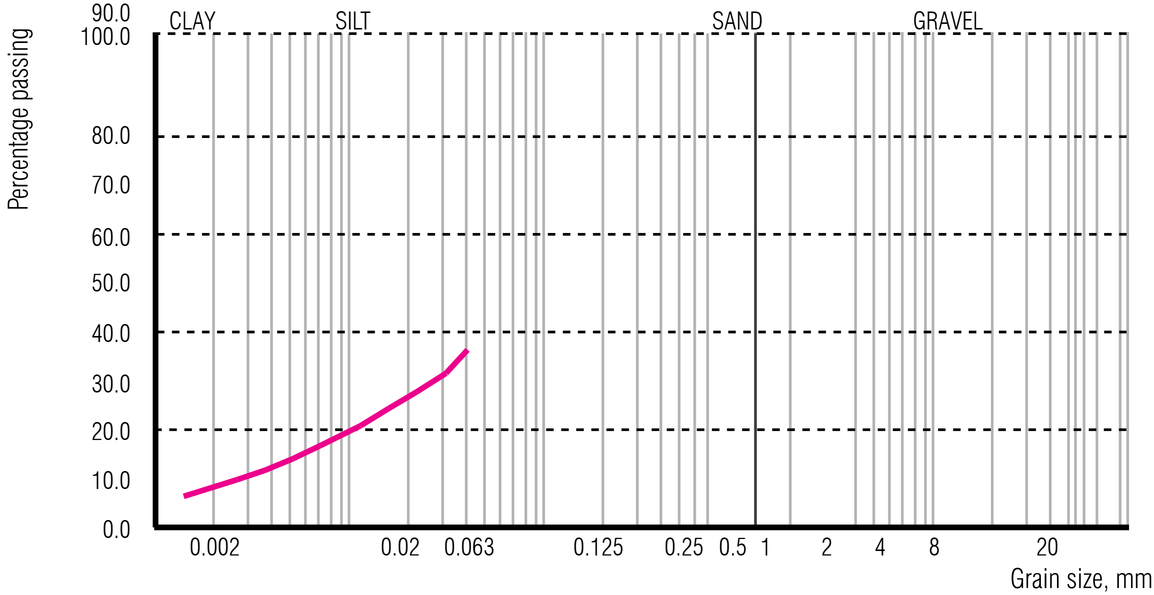
To make the laboratory tests I had the support of the Geotechnical Department at Chalmers University of Technology. We used the same soil that was utilised in the site tests.

First I took the samples, without sieving, and made a Sedimentation Test. Tthe earth was let to dry for 24 hours under a temperature of 180 Celsius degrees. This in order to eliminate the water particles present in the mixture and be able to weight each sample.

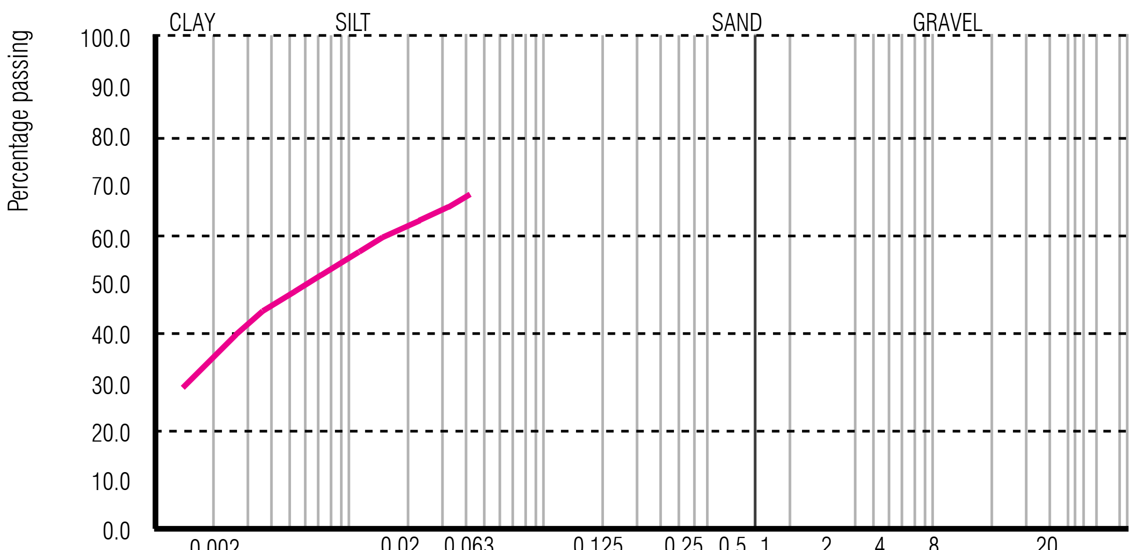
The samples are dried Win ovens at a temperature of 180 ºC (David Martínez Escobar 2013)


Once the earth was dry, we put the samples in 4 different tubes with a solution of water and phosphate, a mix that helped to separate the particles of clay, silt and sand.

The result of our experiments are shown in next page´s graphics. We technically proved that the earth from Gothenburg had a low content of clay, around 10%, in comparison with the earth from Sjövik that had 50% of clay and silt content.




Gothenburg Sample




Sjövik Sample

Sedimentation test, a solution of water and phosphate helps to separate clay, silt and sand particles. (David Martínez Escobar 2013)

Based on the laboratory experiments, the sample from Gothenburg has approximate 10-15% of clay. The sample from Sjövik has a high content of clay and silt, around 50%, the addition of sand should be considered if someone would like to build with this soil. A good proportion to build with rammed earth should be close to:

**30% CLAY/SILT** + **70% SAND/GRAVEL**

## CONCLUSIONS

To be able to build with earth, it is necessary to have experience and skills in the field. There are soils that can be instantly discarded when feeling the mixture with our hands, observations developed with knowledge gathered after years of practice.

It is recommended, in any case, to count with the support of specialized areas, like geotechnical institutes or laboratories. This is a disadvantage if we compare earth technologies with cement technologies, concrete is easy to produce, and standardization makes it easy to apply almost in any situation.

(part 4)

# TECHNICAL CHARACTERISTICS

# GENERAL CHARACTERISTICS OF RAMMED EARTH

In order to have a better understanding of the physical properties of loam, the general characteristics of rammed earth are analyzed in this chapter and compared to those of concrete and other commonly used materials like wood or bricks.

It is difficult to analyze rammed earth and concrete under the same parameters, the applications of concrete are wide, the strenght and sheer capacity is by far higher than any other building material.

It would be difficult, if not imposible, to build a dam of rammed earth, in this case. Like in bridges or large-scale projects, concrete is the best option. But for other purposes, such as residential or commercial buildings, rammed earth could work as perfectly as concrete, wood, or bricks do.

*The Natchez Trace Parkway Bridge, Tennessee*
(Mudd 2010)

With this analysis we will understand that concrete is not our enemy, but in many cases is over-used. Concrete helped man to build bridges and roads, which is positive, but the explotation of this material also slowed down the evolution of other technologies.

*It is above all emerging and developing countries that suffer huge deficits in housing construction. Today these countries account for 85% of the yearly global consumption of cement and concrete. Today cement-bonded concrete building material has become the most important "human necessity" after water – in global terms we annually use three tons of it per head of the population.* (Kapfinger, Singer 2010)

## COMPRESSIVE STRENGTH

The density of a rammed earth wall lies between 1,700 and 2,400 kg/m$^3$ for a load bearing structure. Concrete´s density can be up to 2,350 kg/m$^3$.

Rammed earth for loadbearing applications should have a compressive strength of 2 N/mm$^2$ (Röhlen, Ziegert 2011). A material with sufficient abrasion resistance should count with a compressive strength of 1.5 to 2 N/mm$^2$.

*Typical bulk density in construction

| | RAMMED EARTH | CONCRETE |
|---|---|---|
| Bulk Density* | 2,000 kg/m$^3$ | 2,350 kg/m$^3$ |
| Compressive strength | 2 - 4 N/mm$^2$ | 17 - 30 N/mm$^2$ |

In collaboration with the Geotechnical Department of Chalmers University of Technology I made several compression tests with the soil sample from Göteborg, without the addition of aggregates. The results we got were close to the levels of permissible compressive strength for rammed earth elements, reaching force of 1.8 N/mm$^2$. This information is used as a reference that soil in Göteborg is suitable to use in earth buildings.

Compressive test performed in Chalmers´ Getechnical Laboratory (David Martínez Escobar 2012)

## TENSILE STRENGTH

Rammed earth structures, like in concrete, do not work under tension.

| | RAMMED EARTH | CONCRETE |
|---|---|---|
| Tensile strength | 0.4 N/mm2 | 2 - 4 N/mm2 |

## SHRINKAGE RATIO

The drying of a rammed earth wall means that the element will shrink. Saying this, a rammed earth structure should not be allowed to dry irregularly or too quick.

Shrinkage in rammed earth elements should not be more than 2%, and for visible elements should not be more than 0.7%

| | RAMMED EARTH | CONCRETE |
|---|---|---|
| Shrinkage ratio | 0.5% - 2% | 0.04 - 0.08% |

## DRYING PERIOD

The period during which wet loam reaches its equilibrium moisture content is called the drying period. (Minke 2009). During the construction process and the drying period the walls should be protected against rain. If environment conditions provide a warm weather and air movement, shrinkage in rammed earth elements can stop after a few days, after three weeks the walls can be completely dry.

| | RAMMED EARTH | CONCRETE |
|---|---|---|
| Drying period(1) | 20 - 30 days | 5 - 7 days(2) |

.

(1) 23 ºC, relative humidity 50%

(2) Even if concrete structures can be dry within a few hours, the curing period is important to increase strength and durability, and it could take from 5 to 7 days, in which the surface should be moist. Concrete´s hardening is due to a chemical reaction between water and cement, which is the result of hydration.

## HEAT TRANSFER

The heat transfer of a material is defined by its thermal conductivity λ (W/mK). This indicates the quantity of heat, measured in watts/$m^2$ that penetrates a one meter thick wall a temperature difference of 1°C.

Building materials that combine high heat capacity, high density and a moderate thermal conudctivity (λ) are good for using their thermal mass in passive building design.

(1) Bulk density of 2,000 kg/$m^3$ in typical works
(2) Bulk density of 2,350 kg/$m^3$ in typical works

| | THERMAL CONDUCTIVITY (λ) |
|---|---|
| Rammed Earth(1) | 1.10 W/mK |
| Reinforced Concrete(2) | 2.30 W/mK |
| Steel | 7,800 W/mK |
| Wood | 0.13 W/mK |

## HEAT CAPACITY

The thermal capacity or heat storage capacity of a material is defined as the amount of heat needed to warm 1$m^3$ of material by 1°C.

(1) Bulk density of 2,000 kg/$m^3$ in typical works
(2) Bulk density of 2,350 kg/$m^3$ in typical works

| | SPECIFIC HEAT CAPACITY |
|---|---|
| Rammed earth(1) | 1.5 kJ/kgK |
| Reinforced Concrete(2) | 1.0 kJ/kgK |
| Steel | 0.45 W/mK |
| Wood | 1.6 W/mK |

Materials like wood have a high heat capacity, but a low thermal conductivity, decreasing the heat absorption rate. Steel can also store heat, but it has a high thermal conductivity, and stored heat will be released too fast. Direct gains in passive solar design is enhanced when the sun directly heats the building´s interior, and heat can be stored by a material with good thermal mass. Under this context, rammed earth is a material that promotes heat gains in building spaces.

## EMBODIED CO2 ENERGY

Embodied $CO_2$ in building materials should consider information about the extraction, refining, manufacturing, transport, installation and eventual recycling of the materials.(Bennett 2010)

The values here presented do not consider transportation, production or site construction. Since these values depend in the type of energy used in the production process, as well as the transport system used to deliver the product, the values in the chart bellow account only for raw materials.

When building with rammed earth is expected to use soil from the site or a nearby area. In this context the embodied $CO_2$ of a rammed earth wall is considered equal as aggregates like sand and gravel. If imported soil or aggregates should be utilized these values would not apply for a rammed earth wall.

In the case of concrete, cement content is only one-sixth. The $CO_2$ Embodied Energy of Portland Cement is shown only as a reference, and is the only concept considering a cradle-to-gate analysis.

| | $kgCO_2/m^3$ | $kgCO_2$/tonne |
|---|---|---|
| Bricks (fired) | 1,895 | 972 |
| Concrete (precast)(1) | 328 | 137 |
| Gravel | 19 | 10 |
| Portland cement(2) | - | 930 |
| Rammed earth(3) | 19 | 10 |
| Sand | 19 | 10 |
| Steel | 26,870 - 54,497 | 3,455 - 6,987 |
| Straw bale | 4 | - |
| Wood | 147 | 104 |

(1) With reinforcement
(2) Only concept in the chart with a cradle-to-gate analysis
(3) Without formwork

## TIME INPUT

The time input to build a rammed earth element varies, depending in the construction method used for a specific case. In traditional rammed earth walls constructed manually, including preparation, transportation and construction is from 20 to 30 h/$m^3$ (Minke 2009). If mechanized process and improved technique are enhanced, the time could be reduced up to 10 h/$m^3$.

In the book *Earth Building Practice. Planning, designing and building*, Röhlen and Ziegert describe that in rammed earth the time to build could take from 6 to 20 h/$m^2$, depending if is a mechanized or manual process.

There is no precise number about the working time, much depend in the formwork system selected to build, strongly related to the economic capacity of a project. The skill and experience of the crew when building with rammed earth is a key factor to determine the time.

Another important component for time calculation is the appearence of the walls, in the case of the houses in Steninge it took only 2 h/$m^3$ to build the walls with a crew of five people. But it was planned to cover the walls with a clay plaster, time could be saved in formwork preparations and ramming process. If rammed earth is to be exposed, careful and uniform ramming is expected, as well as a perfectly designed and faultless formwork.

| | RAMMED EARTH | CONCRETE |
|---|---|---|
| Non-exposed wall* | 2-6 h/$m^3$ | 10 min/$m^3$ |
| Exposed wall* | 6-10 h/$m^3$ | |
| Non-exposed wall | - | |
| Exposed wall | 20-30 h/$m^3$ | |

*Time input improving formwork and using pneumatic rammers

## SUMMARY - CONCRETE AND RAMMED EARTH

| | RAMMED EARTH | CONCRETE |
|---|---|---|
| Density | 2,000 $kg/m^3$ | 2,350 $kg/m^3$ |
| Compressive strength | 2-4 $N/mm^2$ | 17-30 $N/mm^2$ (1) |
| Tensile strength | 0.4 $N/mm^2$ | 2-4 $N/mm^2$ |
| Shrinkage ratio | 0.5%-2% | 0.04 - 0.08% |
| Drying period(2) | 20-30 days | 5 - 7 days |
| Thermal cond. ($\lambda$) | 1.10 W/mK | 2.30 W/mK |
| Heat capacity | 1.0-1.5 kJ/kgK | 1.0 kJ/kgK |
| Time input | 10-20 $h/m^3$ | 10 $min/m^3$(3) |
| Embodied $CO_2$ | 10 $kgCO_2$/ton | 137 kg $CO_2$/ton |

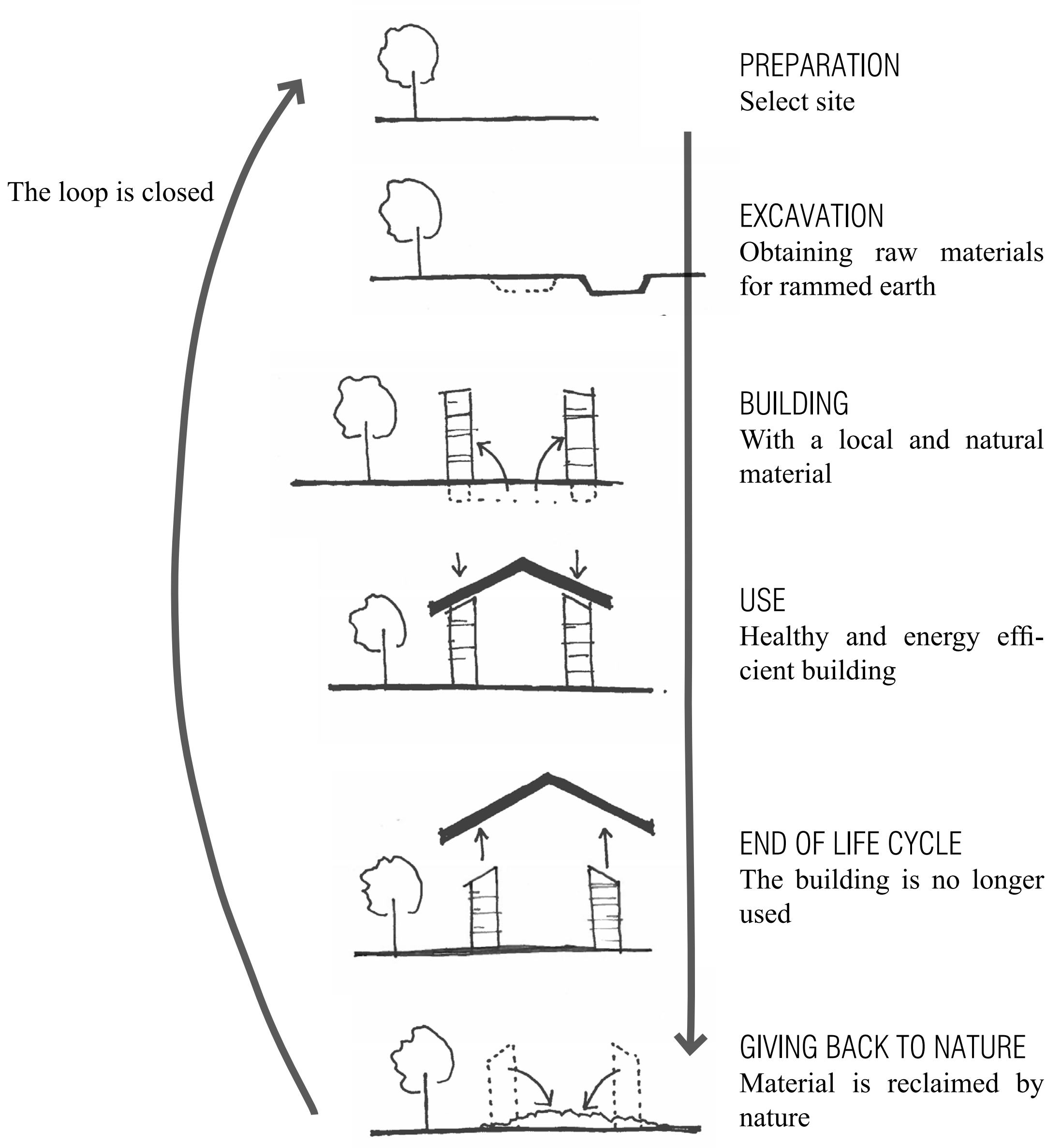
(1) For standard purposes, but this value can go up to 50 or 60 $N/mm^2$ for some applications
(2) 23 °C, relative humidity 50%
(3) Based on personal experience, without considering time for formwork
Sources: Bennet 2010; Minke 2009; Röhlen, Ziegert 2011

## CLOSING THE LOOP

Analysing physical characteristics of a material should also consider life cycle analysis. What happens to a building material after this reaches the end of this cycle?

In many cases the material could be reused, but how much energy is required to recycle and reuse those materials? In concrete there is an increasing demand for the use of recycled materials like foam glass or crushed concrete instead of gravel. But the Embodied $CO_2$ Energy to produce these aggregates is high and is costly inconvenient today.

Rammed earth is a building technique that allows the material to be reclaimed by nature, after a building has reached the end of its life cycle.



(part 5)

# ARCHITECTURAL QUALITITES

# ARCHITECTURAL QUALITITES OF RAMMED EARTH

A propper analysis of rammed earth as building material would not be complete without considering its architectural qualities. The following pages will illustrate the features of rammed earth as architectonic material.

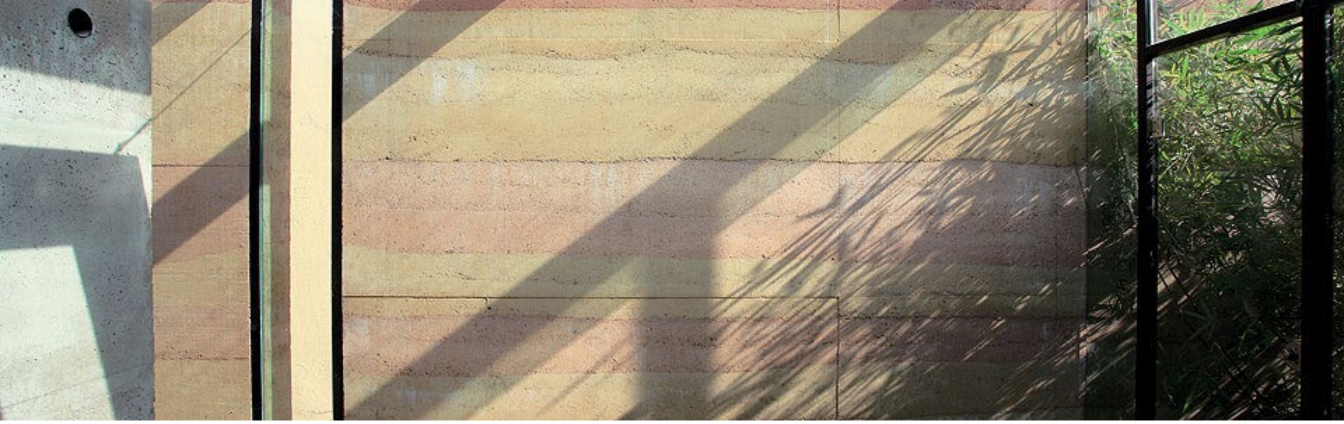
Rammed earth is an undisguised material, one can feel and know what is the wall built with, without hesitating or wondering about the layers behind the surface, this is what makes earth an honest and ecological material.

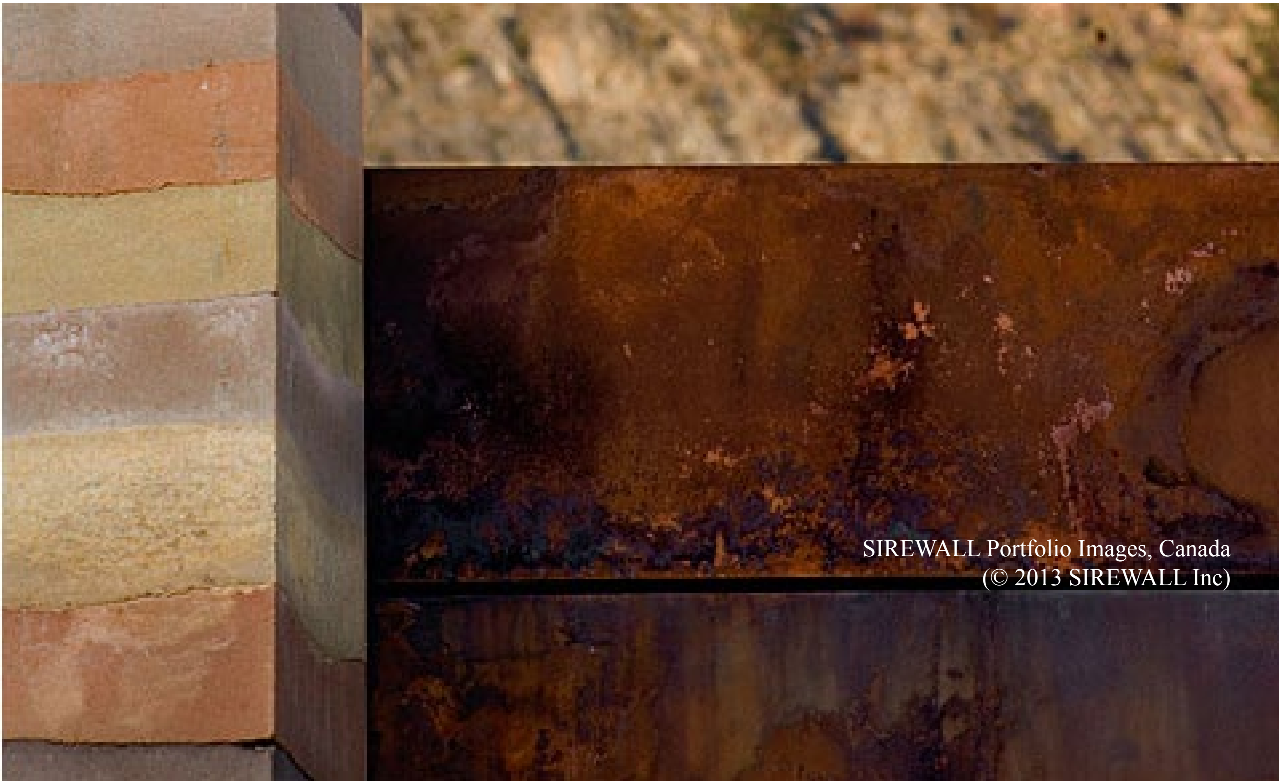
The visible and sensitive attributes of this ancient technique, used today in modern buildings, will be grouped in two main categories: **aesthetic** (colors, texture, form) and **comfort and health.**

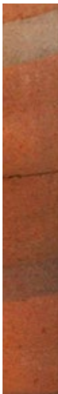
Despite of the technical analysis of rammed earth, we must remember the aesthetic benefits of its use. Rammed earth can be used in houses, offices, commercial and public buildings. Architectural design, interior design and industrial design are few of the areas of application. As architects it would be wise to consider every possible utilization and composition of this material with todays functions and trends.

# COLORS

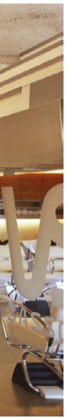
NK´Mip Desert Cultural Center, Canada
Largest Earth Wall in North America
(© DIALOG 2013)

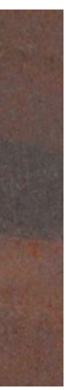


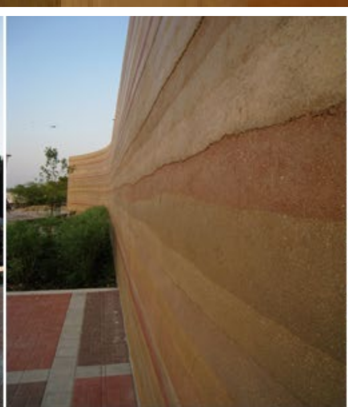


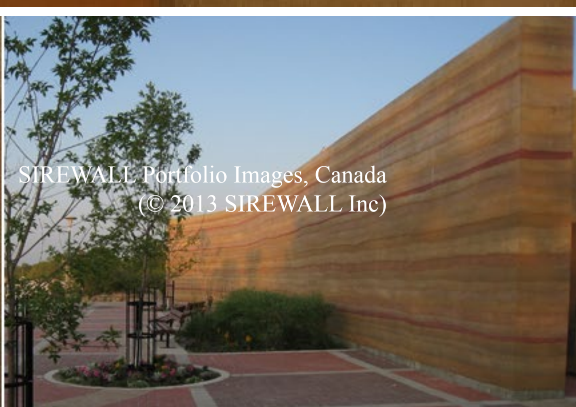


SIREWALL Portfolio Images, Canada



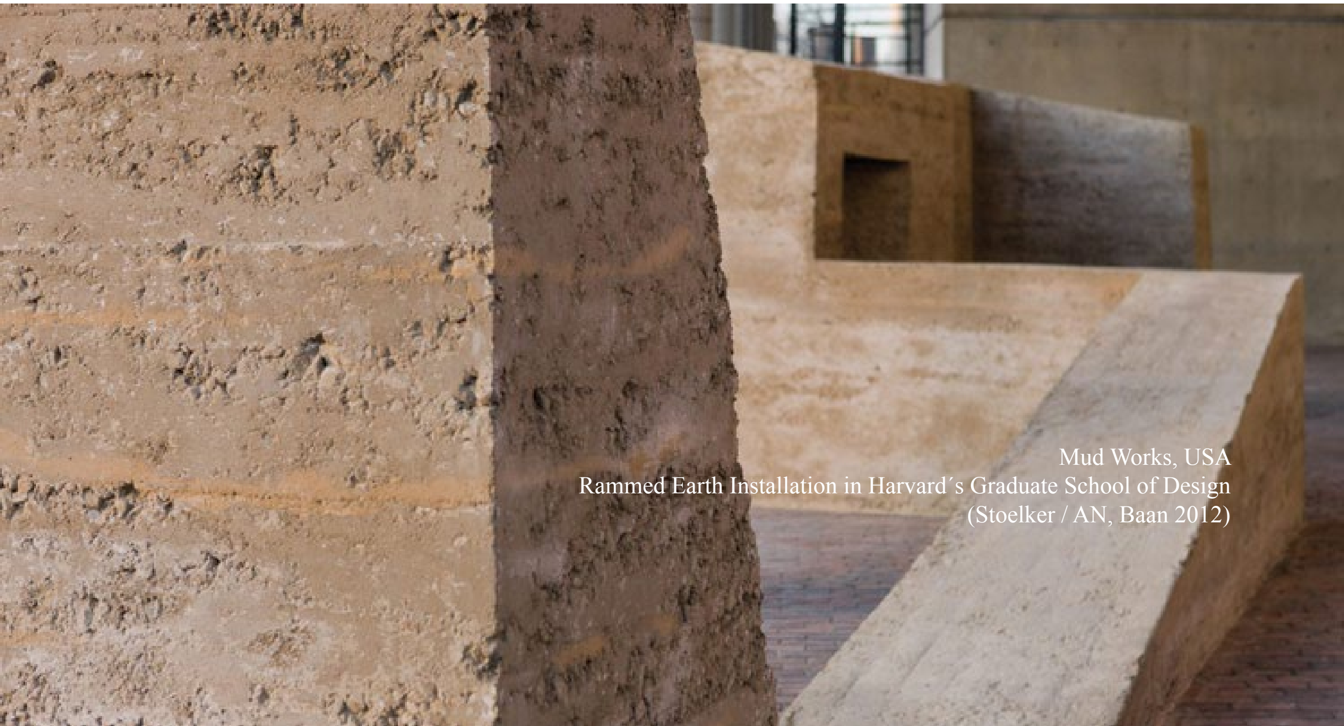






SIREWALL Portfolio Images, Canada
(© 2013 SIREWALL Inc)

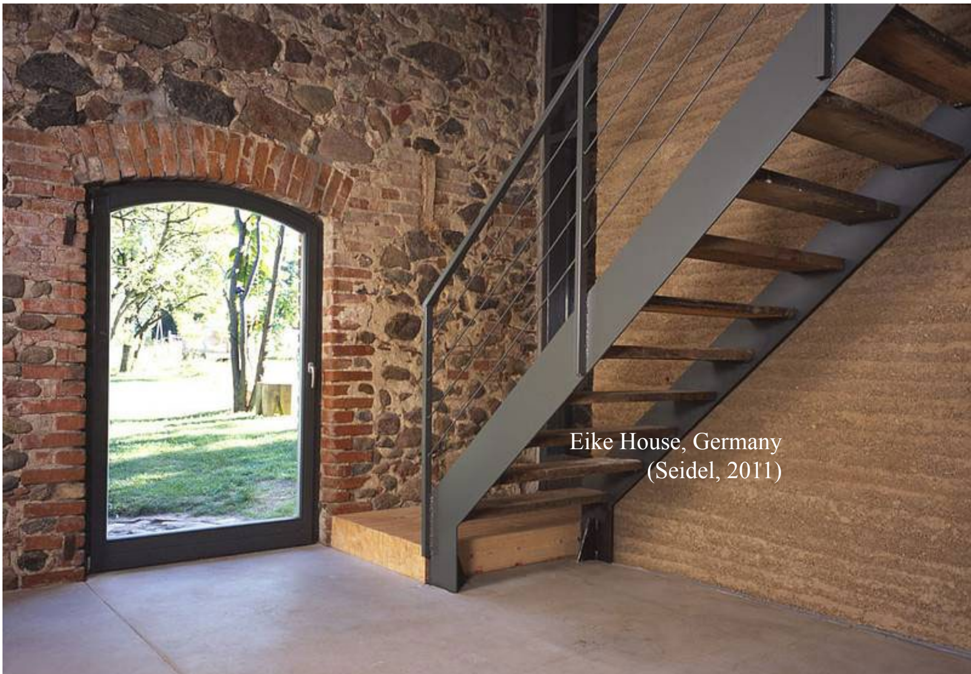
# TEXTURE



Mud Works, USA
Rammed Earth Installation in Harvard´s Graduate School of Design
(Stoelker / AN, Baan 2012)

House Rauch, Austria
(Bühler, Rauch 2008)

Plazza Pintgia, Austria
(Feiner, Rauch 2010)



Eike House, Germany
(Seidel, 2011)

# FORM

Desert Wing House, USA
(© Kendle Design Collaborative)

Zousei Architecture, Japan
(© 2013 Takehiko Nez Architects / Loco Architects)

Lacey Residence, USA
(© 2012 jones studio, inc)

Oaxaca School of Plastic Arts, Mexico
+ Taller de Arquitectura - Mauricio Rocha (Gordo, 2011)

# COMFORT AND HEALTH

When talking about building design, great attention is directed to structural stability, as well as to fire and safety regulations, but less considerations are directed towards healthy and comfortable environments.

Buildings are becoming better insulated and sealed, reducing at the same time air change rates. This phenomena can produce health and comfort complications in buildings. The vapour absorption capacity of earth is higher than any other building material. Earth blocks with high proportion of three layer clay minerals absorb up to 130 g/m2. By comparison concrete has a sorption capacity of approx.  30g/m2. (Röhlen, Ziegert 2011)

This means that earth can regulate humidity variations, when excessive air humidity is caused by heating or cooking, earth can absorb moisture and release it later in the room when this is ventilated, upgrading the indoor room climate.

(part 6)

# URBAN IMPLEMENTATION

# ASSESSMENT

It was described that rammed earth is labour intense, it is not standardized, and has a low insulation value. But it was also demonstrated that rammed earth is natural, is durable and has a strong aesthetical expression. Regarding social aspects, the craftsmanship against automatization should not be left aside.

Our society is moving towards a world that can produce and replace almost everything. Today it is cheaper to buy new furniture than to repare it, labor work is replaced by mechanical processes, and the effect is that we as individuals tend to forget the value of things. Buildings are not excluded. Can craftsmanship be assessed again like it was in the past? Perhaps it is a melancholic thought; on the other hand, if people assess the effort and beauty of building with earth, mud techniques can compete with commonly used materials.

Building with rammed earth can cost 10% more than commonly used techniques; this might seem negative from the economical perspective, but it is positive in the sense that we are paying for work and not for materials, that in many cases come from the other side of the globe, with impacts in transportation and energy.

Like it is described before, we should create a balance in our society between vernacular and technology, where this last one is supporting our traditions.

This is a discussion that may be difficult to extend it, but it is important to reflect in how we live today and how can we live tomorrow. Implementing rammed earth in a urban context is something I would like to promote. To be able to do it we will describe three special charactestics:
-Prefabricated elements
-Reinforced elements
-Insulated elements

# PREFABRICATED ELEMENTS

According to Röhlen and Ziegert, rammed earth it is not widely used in practice, a fact that can be attributed to the high cost of construction.

As an ancient technique that utilizes local materials and minimizes the import of energy-demanding components, what is expensive in rammed earth is not the natural resources. Costs in labor work can be high due to the fact that it takes more time to build with this technique than other "commonly" used methods like concrete or wood.

AVERAGE TIME IN RAMMED EARTH CONSTRUCTION
2-6 hr/m$^3$ - non exposed walls*
6-10 hr/m$^3$ - exposed walls including formwork installation, mechanized construction
20-30 hr/m$^3$ - exposed walls including formwork installation, manual construction

AVERAGE TIME IN CONCRETE CONSTRUCTION
Time - 10 minutes per cubic meter

In developing countries where labor work is accessible, typical techniques of rammed earth are costly-convenient, and is something that builders search.

In industrialized countries a different approach is necessary, we live in a society where everything is standardized and rapidly produced.An alternative for rammed earth in developed countries is the prefabrication of wall elements.

A system that allows us to produce elements almost all year round without the dependency of the weather. The process would be the same, using natural and local materials, but produced in a “workshop”, where temperature can be regulated and propper regulation tests can be performed.

## PLAZZA PINTGIA - ALMENS, SWITZERLAND

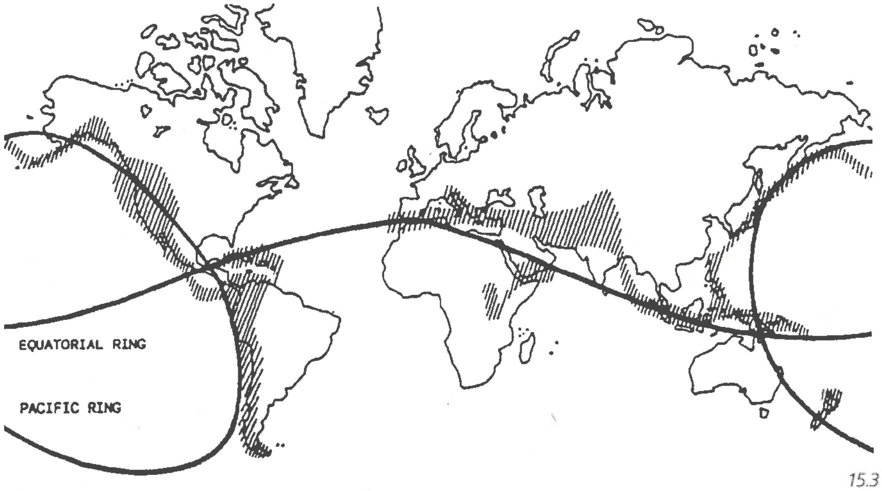
Building period, 2010

Located in the village of Almens, the barn “Plazza Pintgia” was converted into a dwelling-house. The use of prefabricated rammed earth elements divides the area in the house, the 50cm thick walls give the building storage mass, serving as heating and cooling panels that control moisture at the same time. A rammed earth chimney with its heated seat gives the house a nice town center.

*Stable Plazza Pintgia*
(Feiner, Rauch 2010)

The rammed earth elements are assembled and the joints are filled with the same soil, becoming almost invisible.

Stable Plazza Pintgia
(Feiner, Rauch 2010)




The world´s most earthquake-prone regions
(Minke 2009)

# REINFORCED ELEMENTS

It is not earth as a building material which is responsible for structural failures, but instead the structural system of a given building and the layout of its openings. (Minke 2009)

Throughout history, many ancient buildings of earth have withstood strong earthquakes, for example the Hakka Houses (see page 46). These houses like many others in the past were designed integrating bamboo or similar materials as reinforcement of the rammed earth walls.

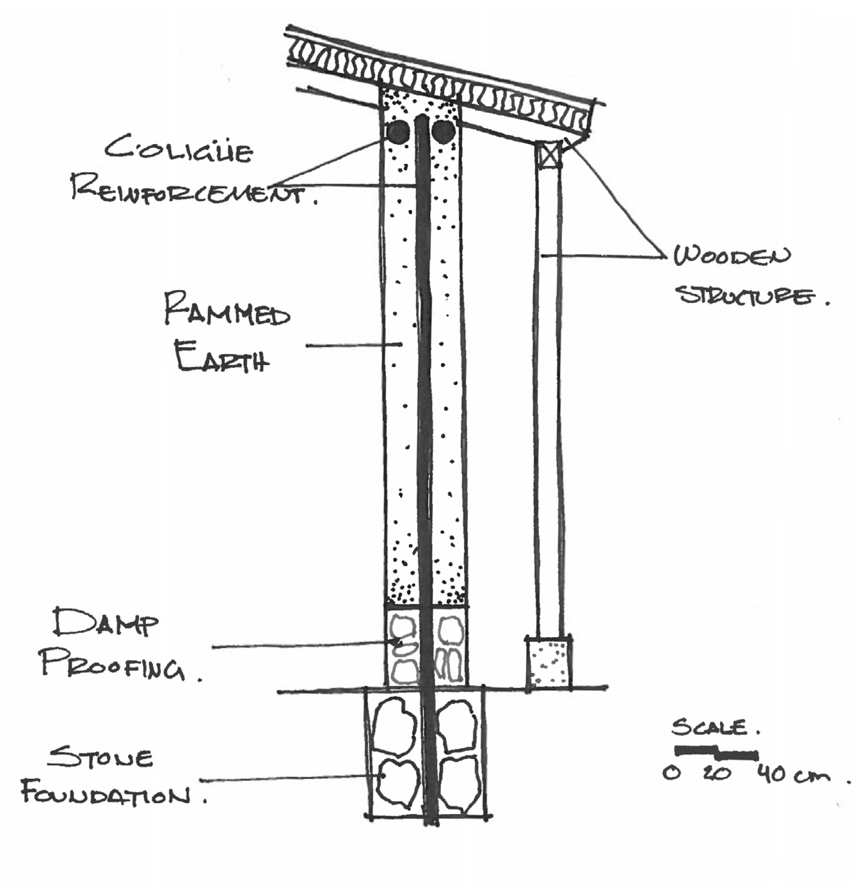
Like in concrete, rammed earth works with compression and not with tension, the use of materials that add tensile strenght to the composite material is recommended in zones that are prone to earthquakes.

As we see in the picture above, Sweden might be far away from the earthquake-prone regions, but it is important to consider reinforced elements for special applications. If we would like to integrate rammed earth in an urban context, creating larger structures, reinforced elements could be implemented in our designs.

In 2001 the Building Resaearch Institute of Kassel University (Germany) in collaboration with the University of Santiago de Chile, built a low-cost housing project using reinforced rammed earth walls.

The system was designed to separate the roof and the wall units. The layout of the plan used “L” and “U” shaped elements that stabilize themselves with the form.

A material similar to bamboo was used to add stability, *coligüe* of three to five cm in diameter serves as vertical reinforcement.




Rammed earth villa in Whistler, Canada. The house was built in 2010 by RDC Fine Homes, using 5% of cement as stabilizer. (© 2013 rdcfinehomes.com)

# INSULATION IN RAMMED EARTH

In Ryerson University, Canada, a recent research by Stuart Fix tried to demonstrate the viability of building with rammed earth in a cold environment. He analyzed the feasibility of adopting rammed earth construction in the cold region of the Canadian Prairie.

Canadian winters are cold and snowy, when compared to other areas of the globe. Those found in the prairie provinces of Alberta, Saskatchewan, and Manitoba are the coldest and longest of Canada, (Canada´s National Climate Archives, 2002) with an average yearly temperature around $2.6^{0}$ C.

*A composite rammed earth envelope should provide great thermal insulation, air tightness, indoor air quality, moisture control, and load bearing strength and durability, with suitable material availability for a one or two storey building in these regions.* (Fix 2009)

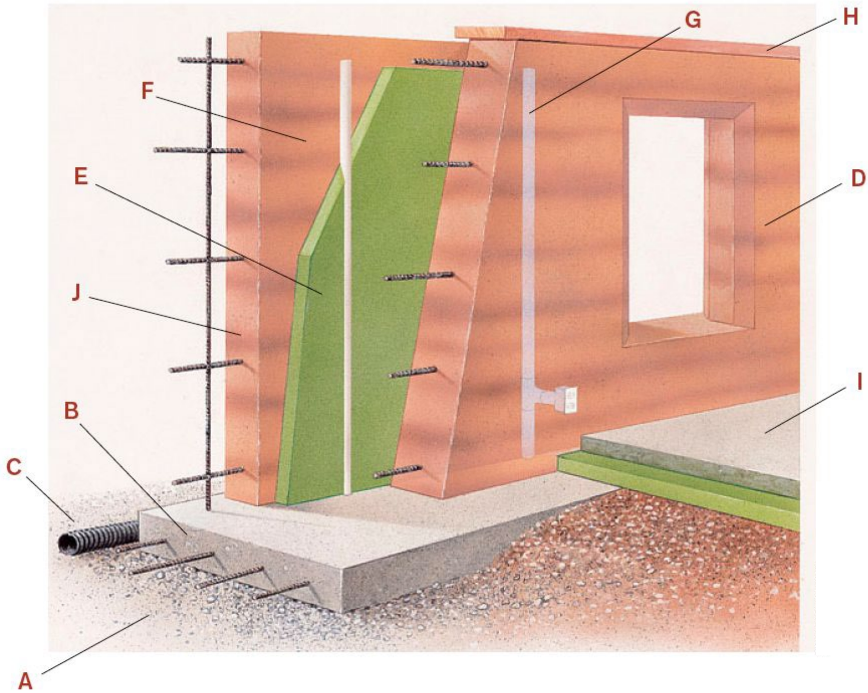
# SIREWALL - CANADA

The SIREWALL System is a method created by Meror Krayenhoff. SIREWALL means *Stabilized, Insulated, Rammed Earth Wall*. In order to build in Canada´s cold climate and according to the norms in that country, the system uses cement as stabilizer and foam insulation in the core of the wall section. The “sandwhich” earth wall is reinforced then with a steel rebar in both sides, interior and exterior.

The U-value of a 30 cm thick rammed earth wall is as much as 1.9 and 2.0 W/m$^2$K (Minke 2009). In cold regions, the addition of insulation should be considered in order to meet building regulations. A rammed earth wall of 32.5 cm thick should have an insulation material (0.04 W/mK) of 14 cm thick. (Röhlen, Ziegert 2011)

In the next page, a wall detail of the SIREWALL system describes the materials used. Some of the materials in the system might seem “non-sustainable”, but it would be interesting to use alternative materials to achieve the same results, for example, using bamboo instead of steel like in the Hakka Houses, perhaps one could sustitute the foam insulation with natural wool or cork.

Prototype rammed earth house by SIREWALL China (© 2013 SIREWALL Inc)




(© 2013 SIREWALL Inc)

SIREWALL SYSTEM

A. Rubble trench

B. Reinforced concrete footing

C. Drain pipe

D. Interior rammed earth wall, reinforced with steel rebar

E. Foam insulation F. Exterior rammed earth wall, reinforced with steel rebar

G. Electrical conduit

H. Wooden top plate

I. Interior floor

J. Sealer to prevent dusting

(part 7)

# RAMMED EARTH IN A LOCAL CONTEXT

# INTEGRATING RAMMED EARTH

Offices constructed with earth from a nearby area is the proposal to integrate pisé in a local context. The project is a personal interpretation of the materials potential to adapt into a urban environment. The importance of this building is not only in earth as building material, but also in the relation between the material and the spaces it creates. The expression of rammed earth is strong, but the message it delivers is also strong.

The design consists in a loadbearing structure of rammed earth in combination with a timber structure; glued laminated beams are proposed due to their versatility and ligthness. The heavy mass of rammed earth will help to store excess heat in the office, and release it when needed.

The name of the building is RE-Office (rammed earth office), we are always looking how to re-use, re-cycle, re-think. Rammed earth is not only a way to re-use soil, it is also a way to give back to nature what we take.

Why it is important to demonstrate that we can build with this technique? I believe industrialized countries should embrace and develop more alternative building technologies, and not the other way around where developing countries accept industrialized processes in construction.

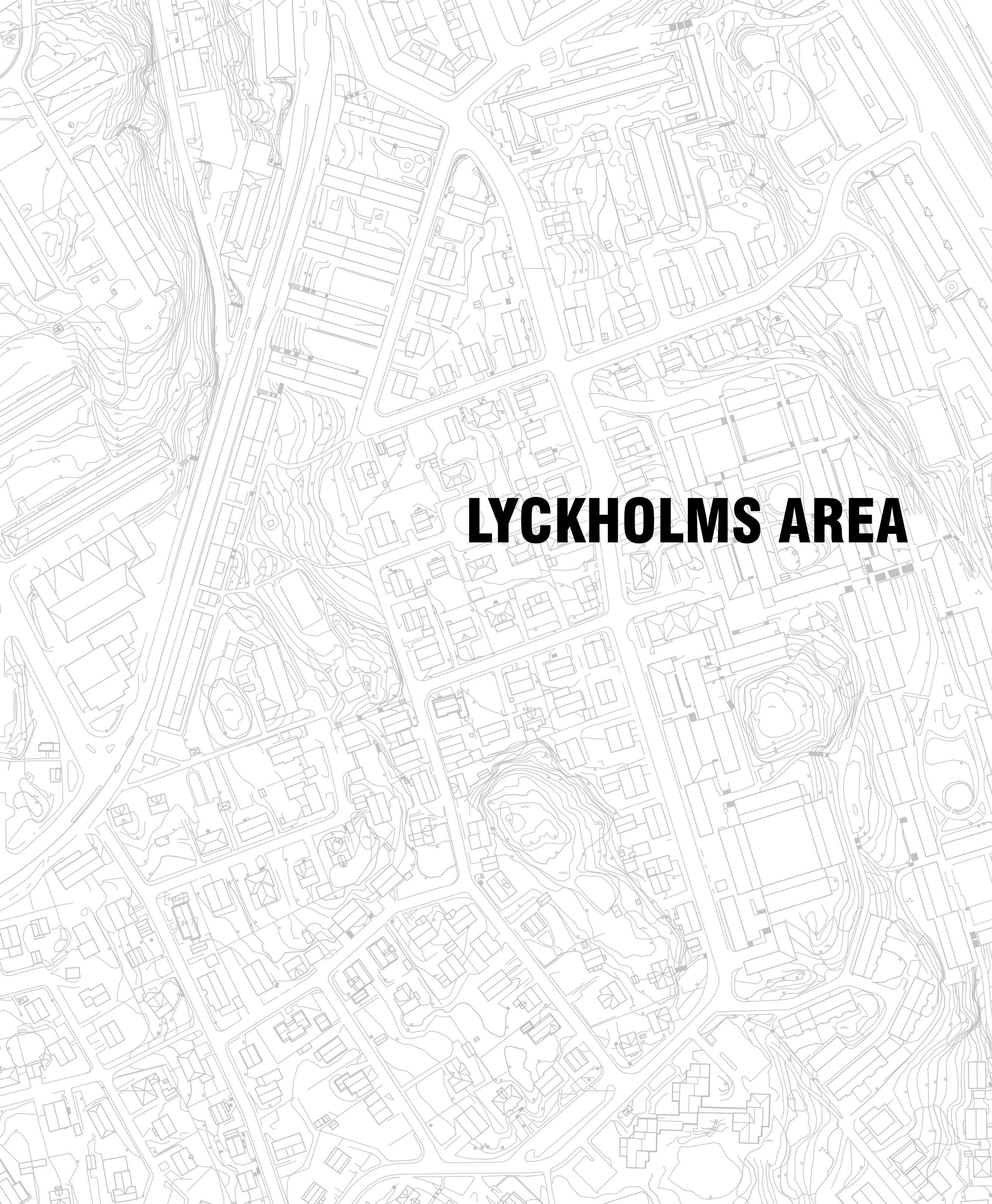
Earth architecture today remains a do-it-your-self technique because there is an abscence of these buildings in urban cities. What is urban could be another discussion, but the lack of earth building constructions in city centers and modern developments is what is important to point out.

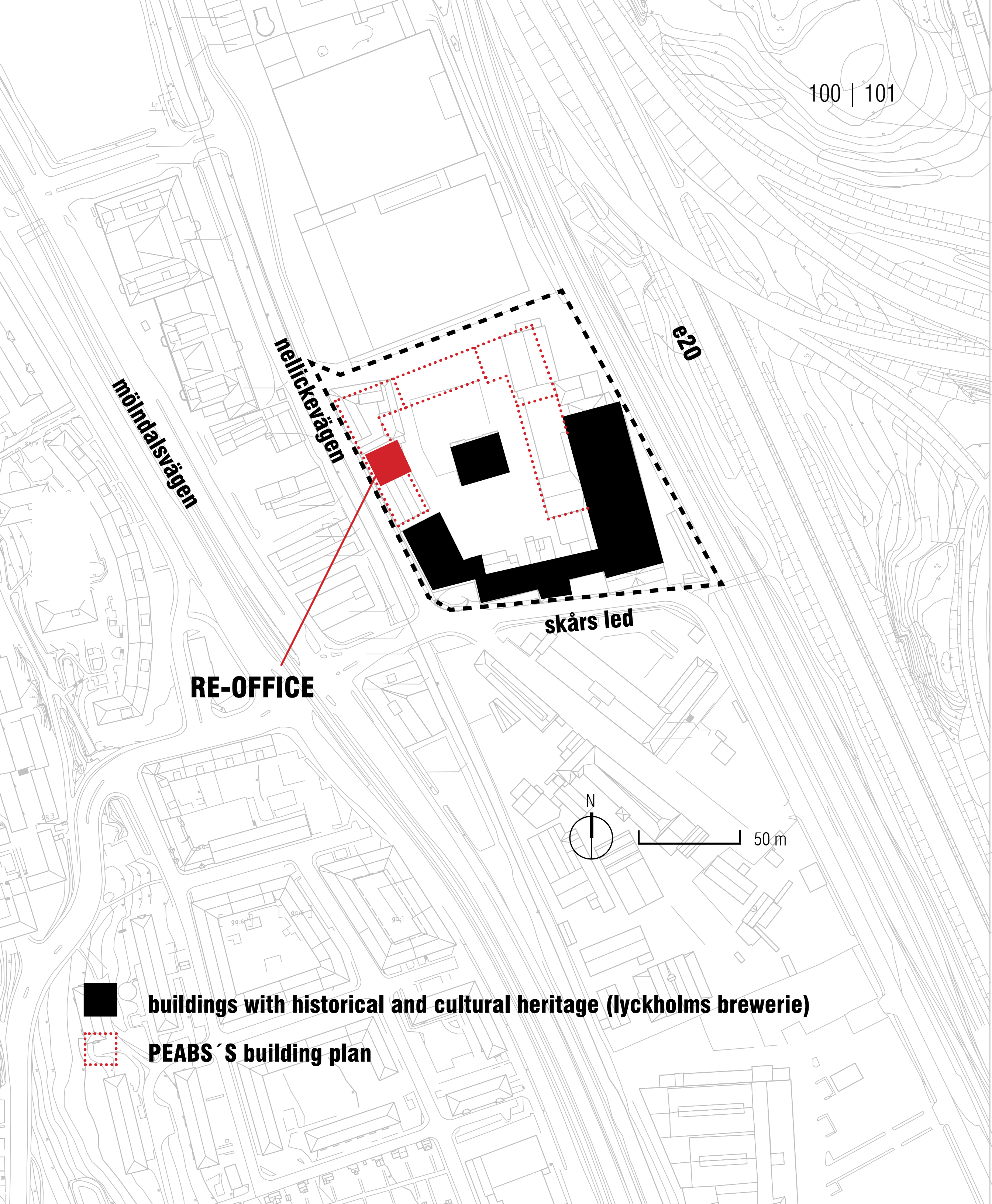
Buildings with natural materials are usually designed to be placed in the countryside. If we, as architects, design and evidence that is possible to build with earth, people will start to notice, and we would be able to see these kind of constructions more and more in our urban areas.

## THE SITE - LYCKHOLMS

The area of Lyckholms is located 3km south from the city center of Gothenburg. It is a site that holds historical buildings with architectural and cultural heritage. The area is close to important green and blue structures, like the Mölndals river. This is the physical space for RE- Office.

# LYCKHOLMS AREA






buildings with historical and cultural heritage (lyckholms brewerie)

PEABS´S building plan

Lyckholms brewerie was founded in the year 1880, some of the buildings were built by that time. Lyckholms brewerie started producing beer in 1881, and it was closed in 1976.

PEAB has been a partner in the Fastighets AB Bryggeriet since the mid 90's, but in April 2012 acquired the remaining 50% stake. PEAB was autorized with planning permission for 19,000 square meters in 2012. This is the first stage of 28,000 square meters of construction for offices.

The plan is to revitalize the area of Lyckholms, mixing commerce in the ground floors and offices in the upper levels, creating in this way a new atmosphere in the area.

RE-Office is located in this area, between the historical buildings and the new development that PEAB is executing. Some of the buildings have been protected, it is important when building to consider the actual character of the site.

Despite PEABs design, the proposal intends to respect the proportions of the existing buildings. If the aim is to revitalize the area and attract more people, the human scale should be taken into consideration.

Lyckholms Brewerie (David Martínez Escobar 2013)

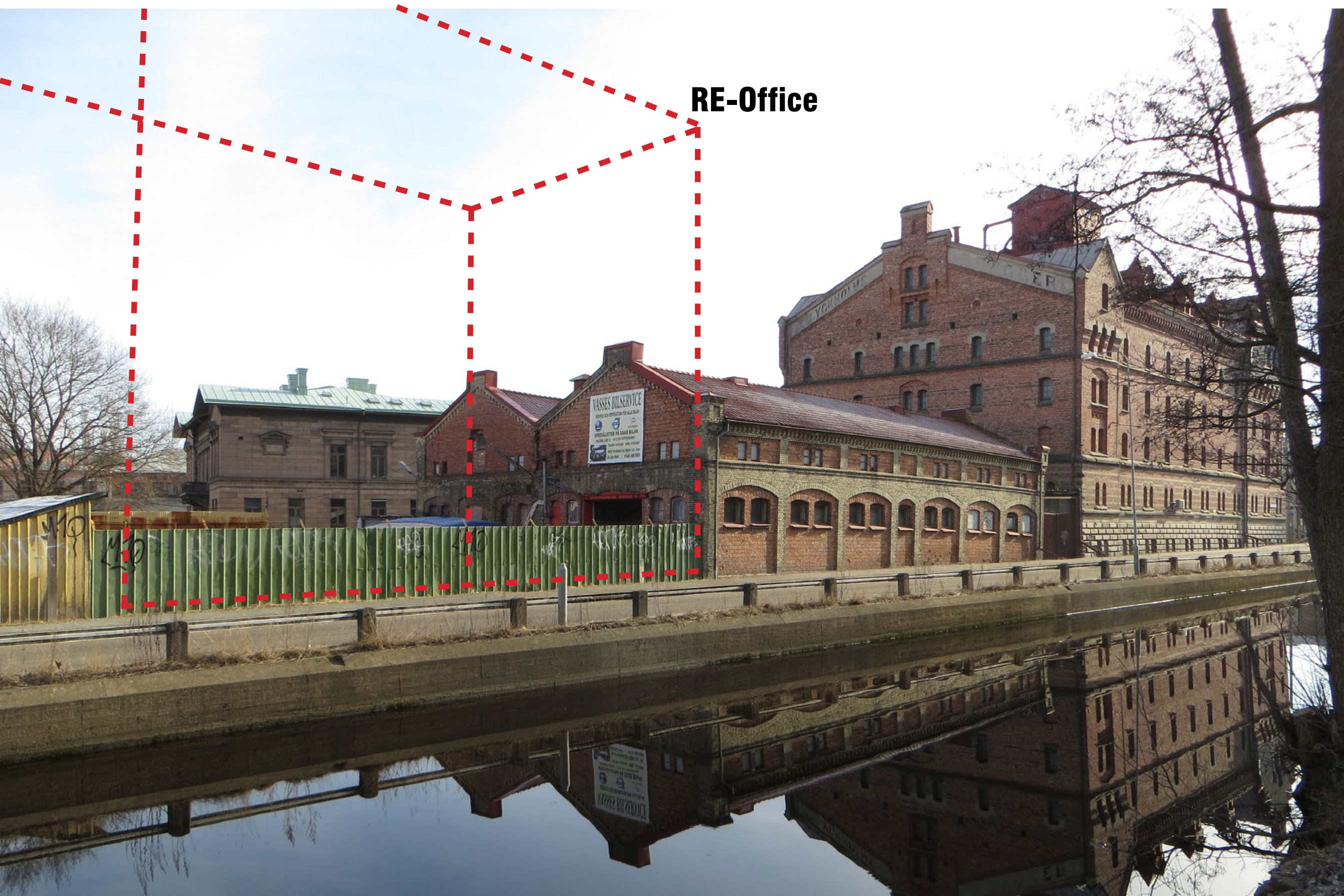
# DELIMITATIONS

RE-Office is located in Lyckholms context, nevertheless a further analysis of the area was not carried out, we have to remember that the main aim of this project is the material, due to the dimension and time input of this investigation it was not possible to make a proper site analysis.

For practical purposes, the design will not take in consideration that the area of Lyckholms is prone to floodings.

The design will, on the other hand, follow the next guidelines:
-The location and relation of the new building with the historical buildings.
-The height of the building and use and will be as the actual detail plan regulates.

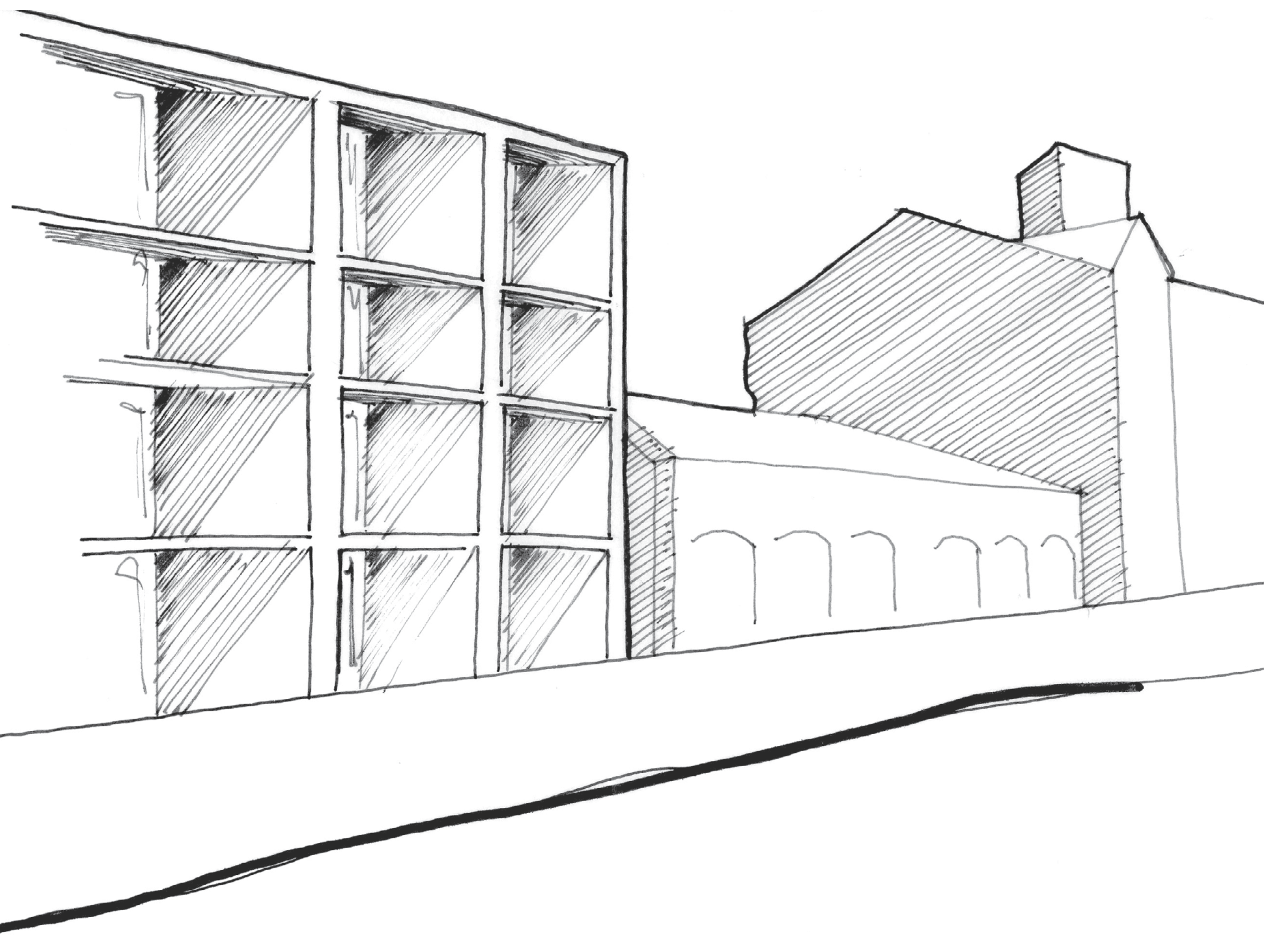
Lyckholms Brewerie (David Martínez Escobar 2013)



How to integrate a new building to an existing structure is not an easy task, even more when the context holds buildings with historical and cultural value.

The area of the building is a lot of 20 x 20m. 1,600 square meters of construction distributed in four levels. A building of mixed functions, with commerce in the ground floor and office spaces in the upper levels, no housing is permited in the zone due to a highway and a busy street that surround Lyckholms.

According to PEAB, the use for the new office buildings are primarily knowledge based companies such as consultants or marketing offices.



# SITUATION PLAN

Property
Historical buildings
PEABs building plan

Existing buildings

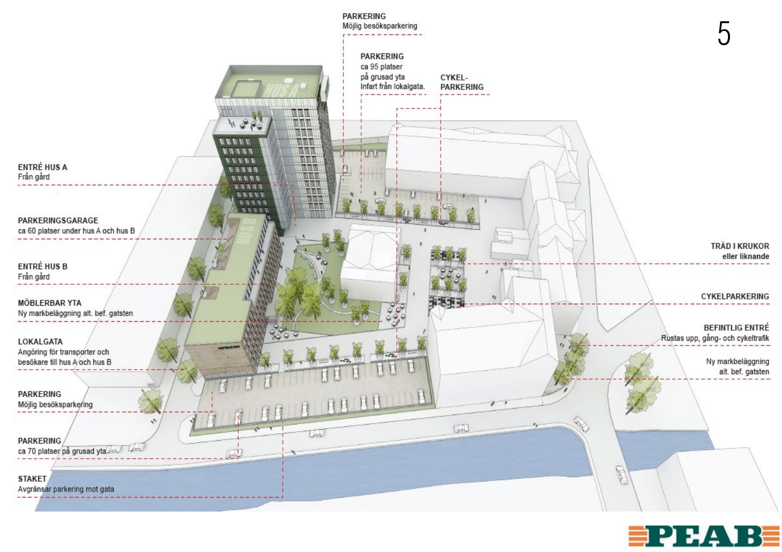
1. Old stables, building that is to be demolished according to the legal plan , place where RE-Office will be placed

2. Main access

3. Founders house and office, today a parking lot surrounds it.

(David Martínez Escobar 2013)



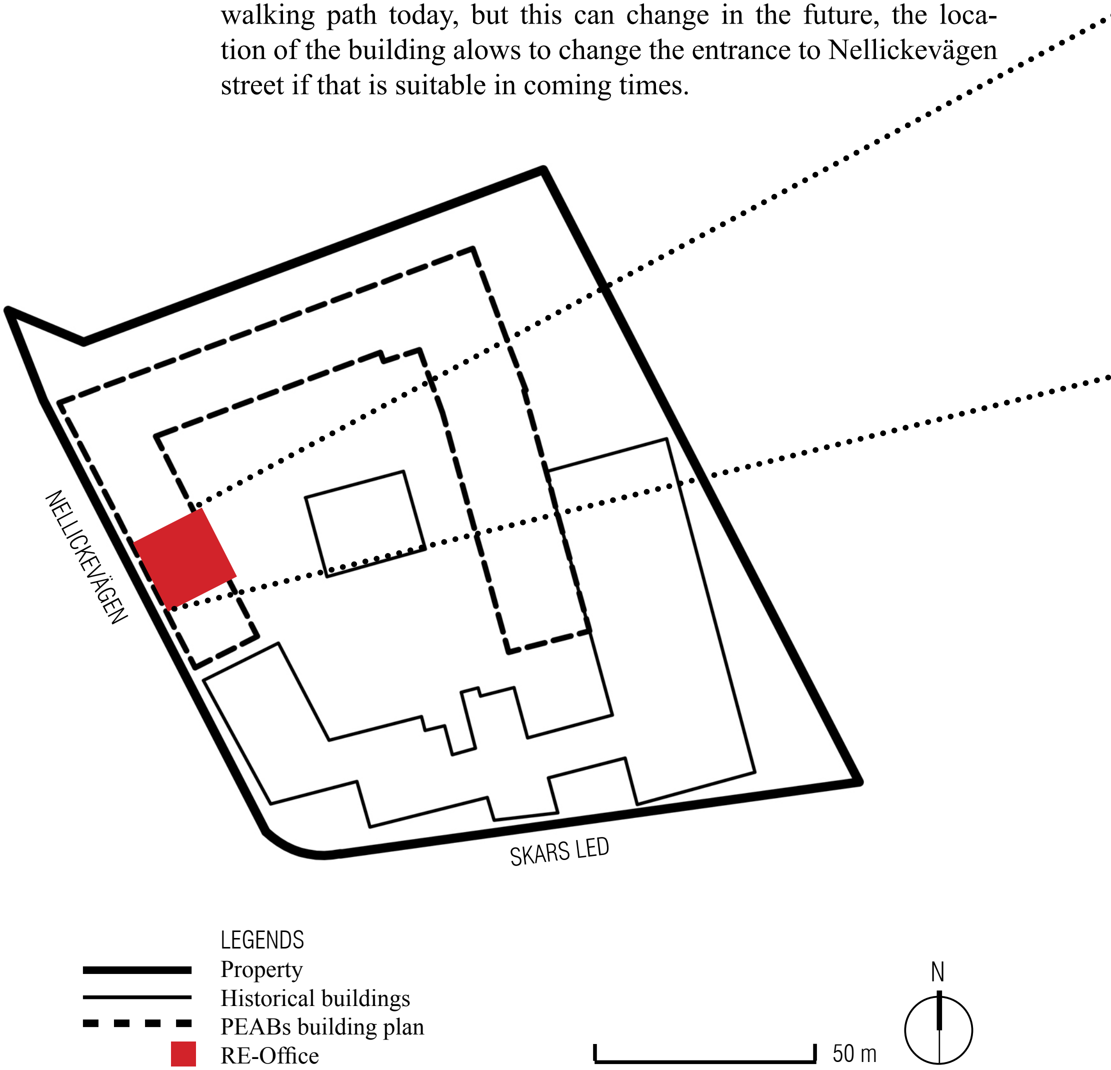



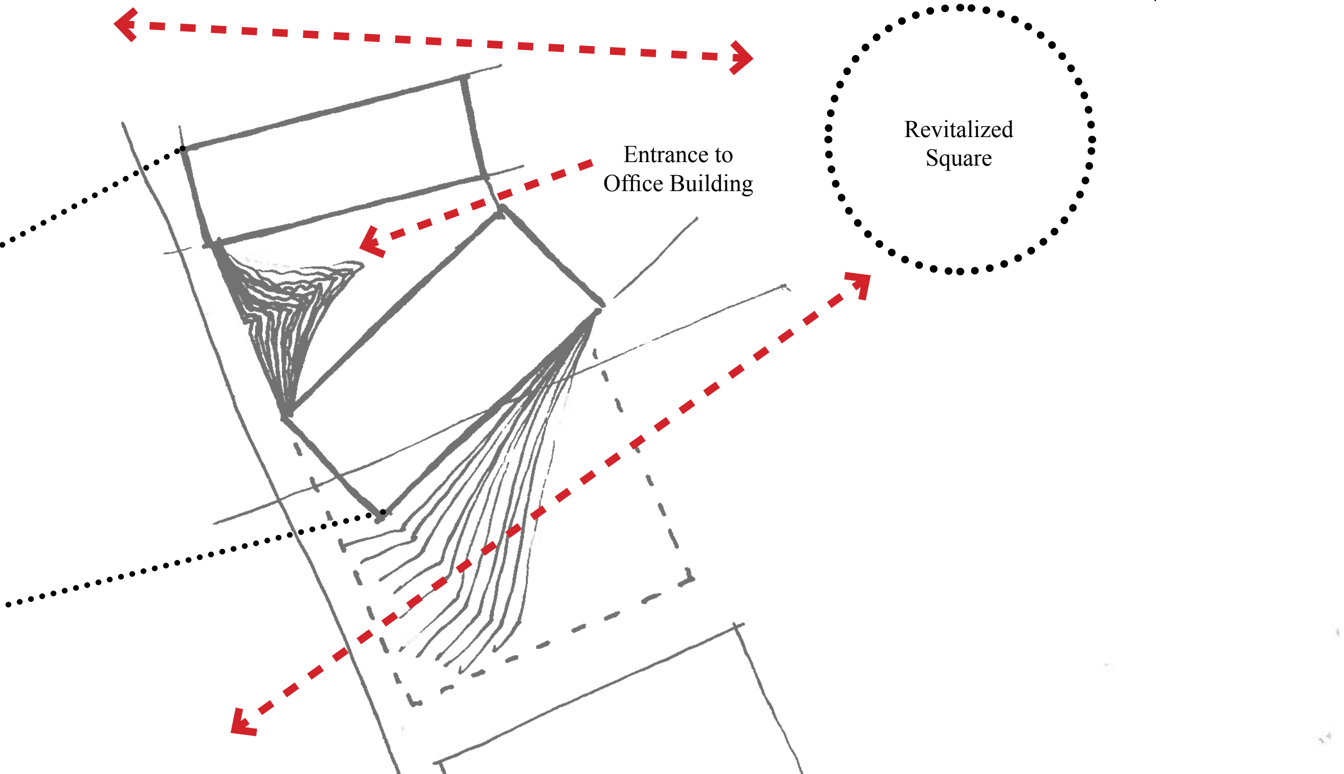

4. Building in front of stables, other side of Mölndals river (David Martínez Escobar 2013)

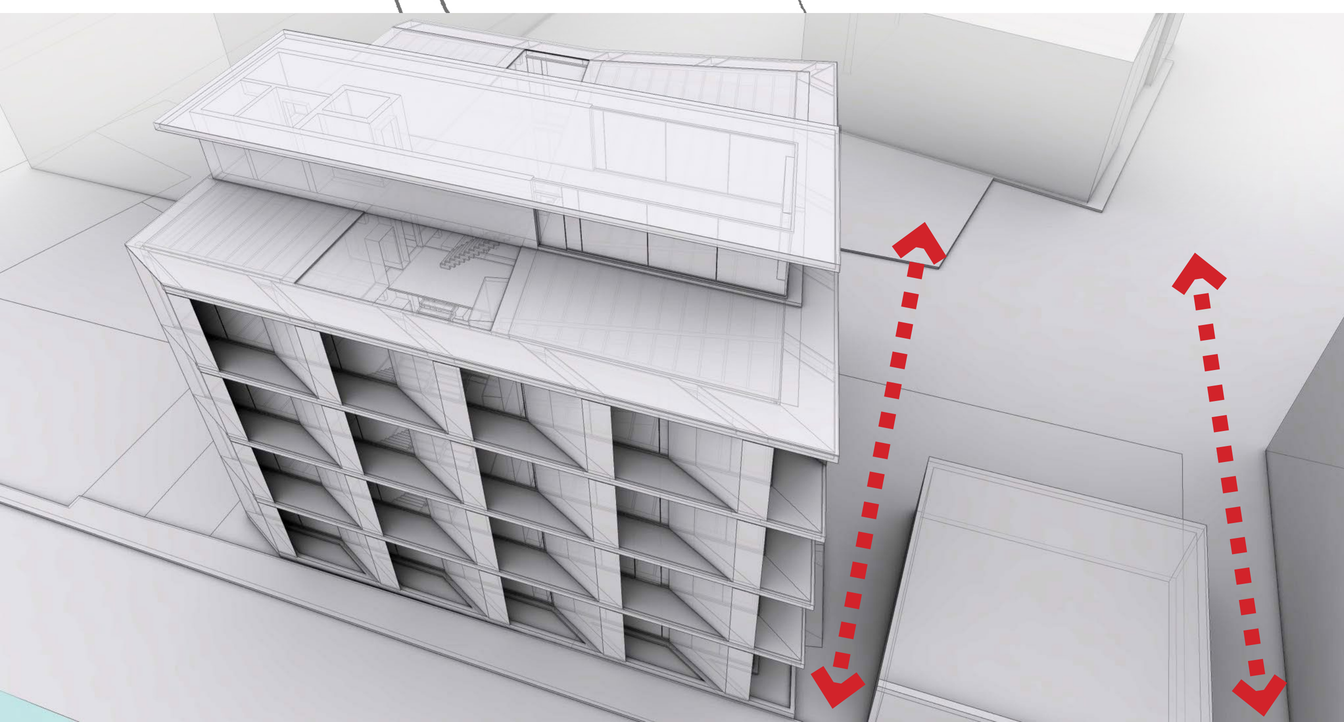
5. PEABs proposal for the first stage of building plan

# SITUATION PLAN

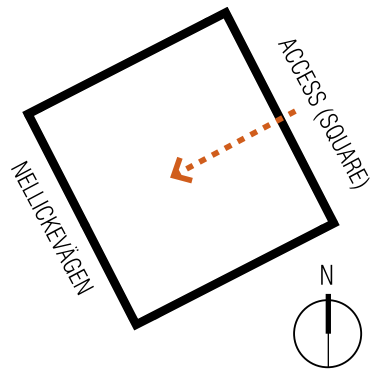
The entrance to the building is proposed through the square, reinforcing communication with other buildings. The position and form of the building will promote the views towards the area of Lyckholms from the street. The street Nellickevägen has not a nice walking path today, but this can change in the future, the location of the building alows to change the entrance to Nellickevägen street if that is suitable in coming times.



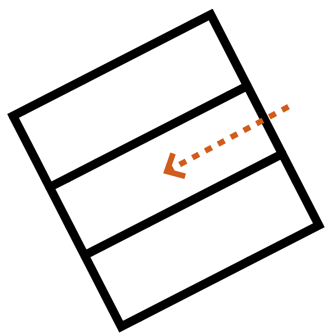

Entrance to
Office Building
Revitalized
Square



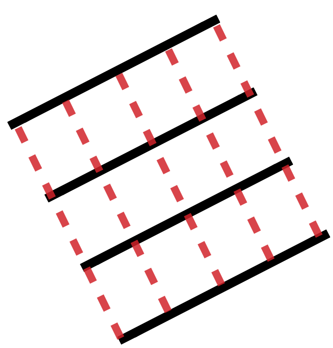
# LAYOUT




The concept is to have a logic relation between material and structure.

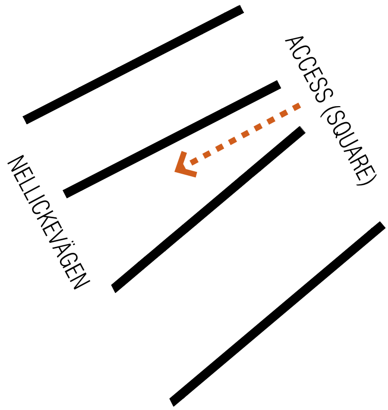


The initial idea is to have four loadbearing walls of rammed earth.

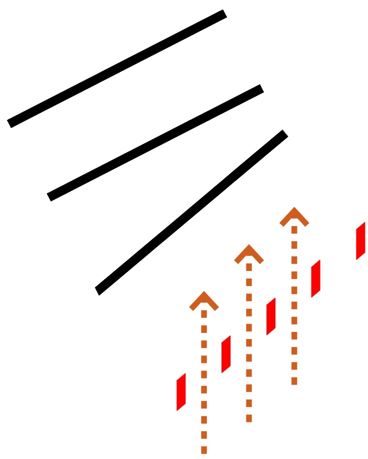


The walls will support a wooden structure.

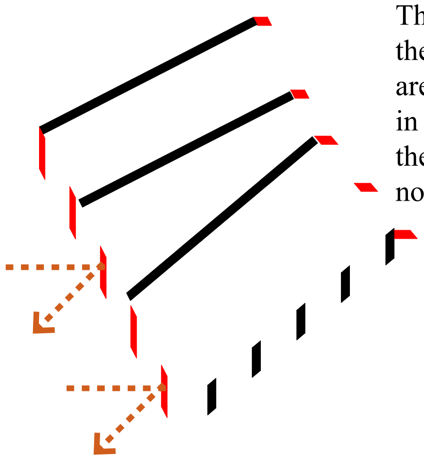
Primary beams



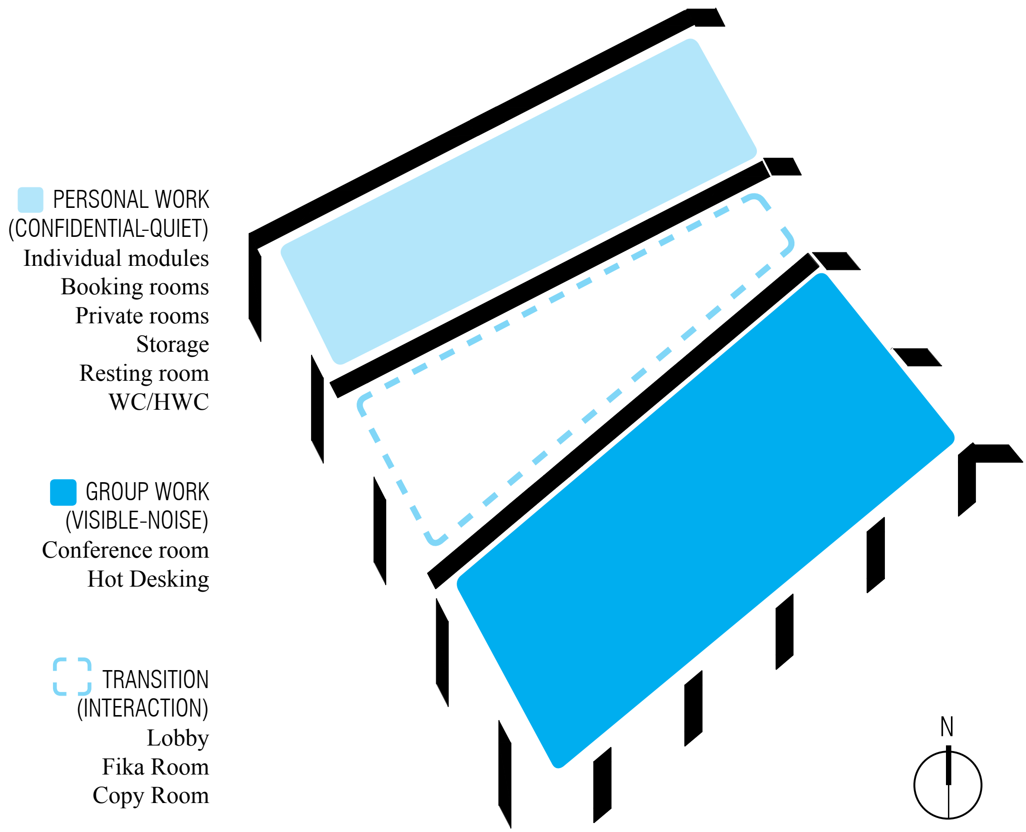

The walls open towards the west and south to take advantage of the views.



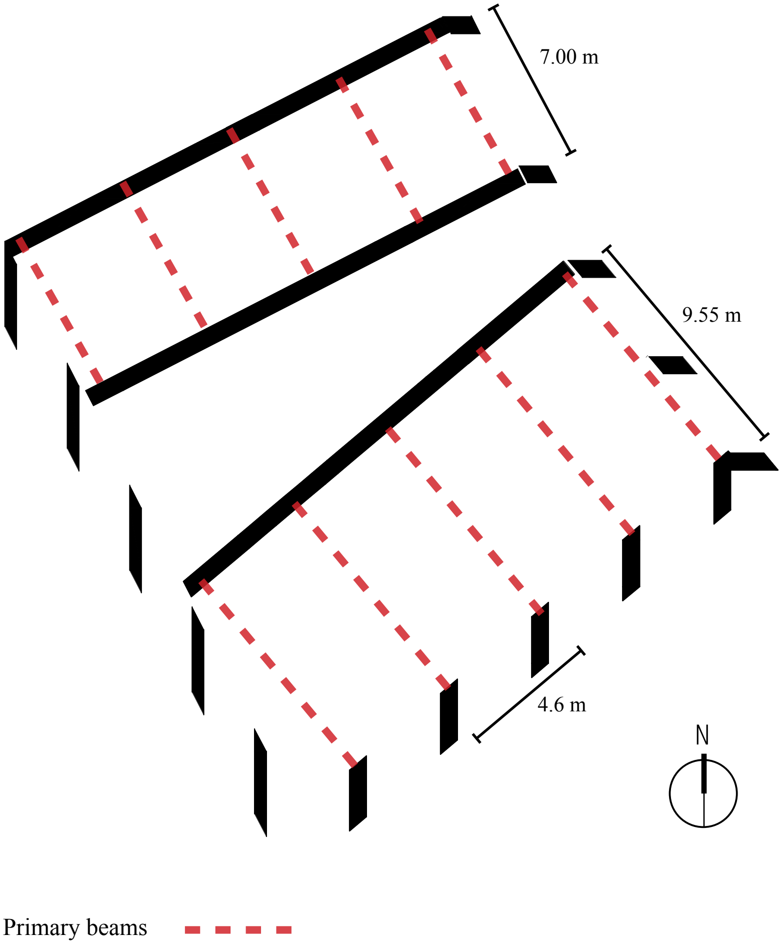
The wall facing south, which is also structural, opens and let the sun to illuminate the office spaces.



The east and west facades follow the same concept, but the walls are not structural. The elements in the west facade help to shade the inner spaces from the afternoon sun.

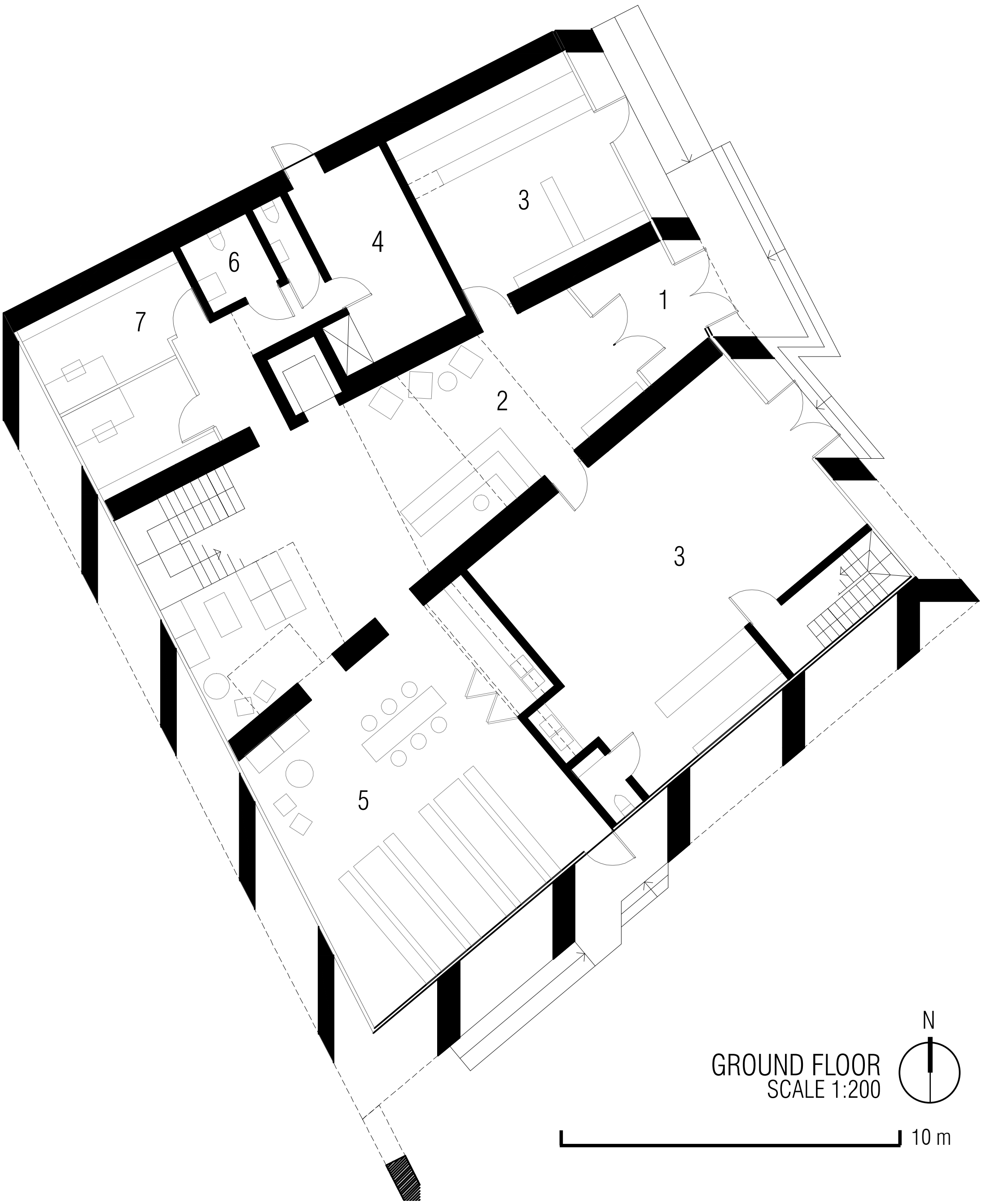



Instead of having an open area with a “sea” full of desks, the layout for the office plan creates a combination of open and close areas, making the inner space adaptable to different functions. An explanation of this design process, according to the functions of the different spaces, is found in the Appendix E of this report.




The design in the flooring and roof system uses glued laminated beams. The main beams have an effective span of 9.55 m at 4.6 m centres and are supporting secondary beams at 0.80 m centres.

It is proposed to use glued laminated beams with dimension of 215 mm x 585 mm as main beams. The beam sizes are according to Swedish standards and a calculation of the structure can be found in the Appendix D of this report, the calculation was performed by Andrea Mossielo, a Masters student at Chalmers.




GROUND FLOOR
SCALE 1:200

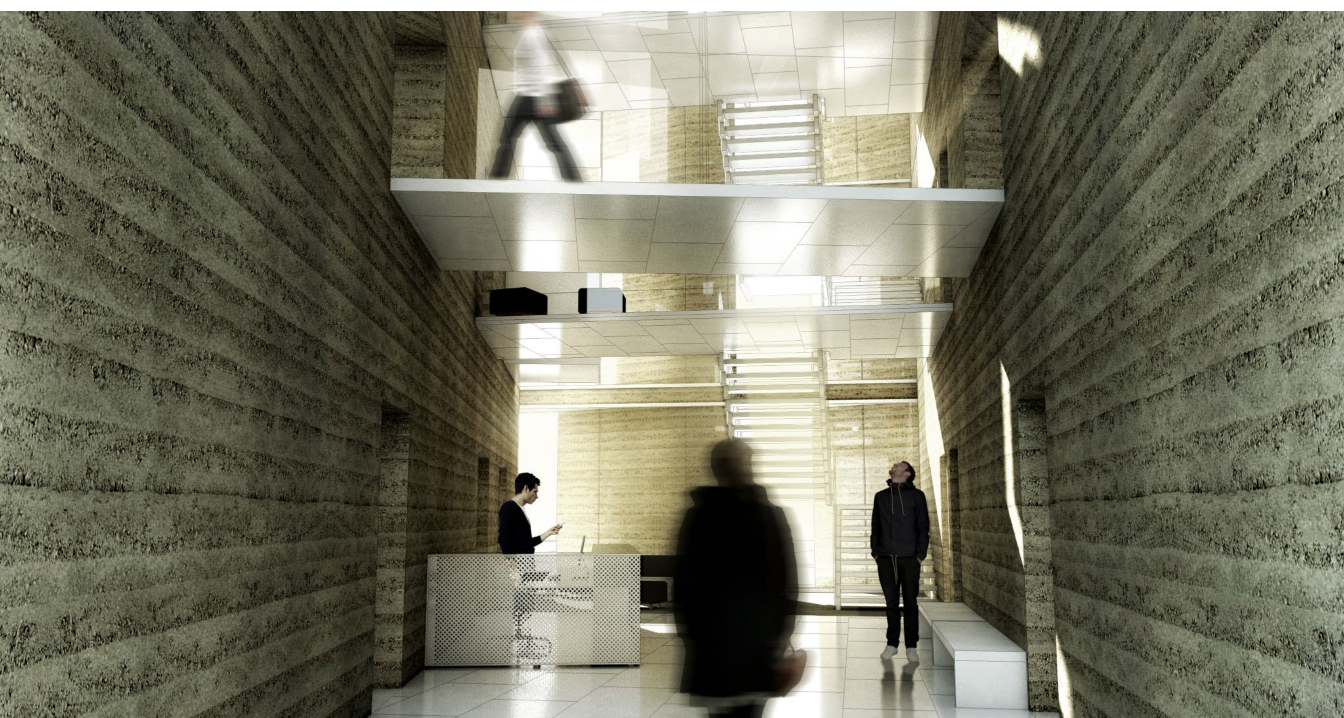
## GROUND FLOOR

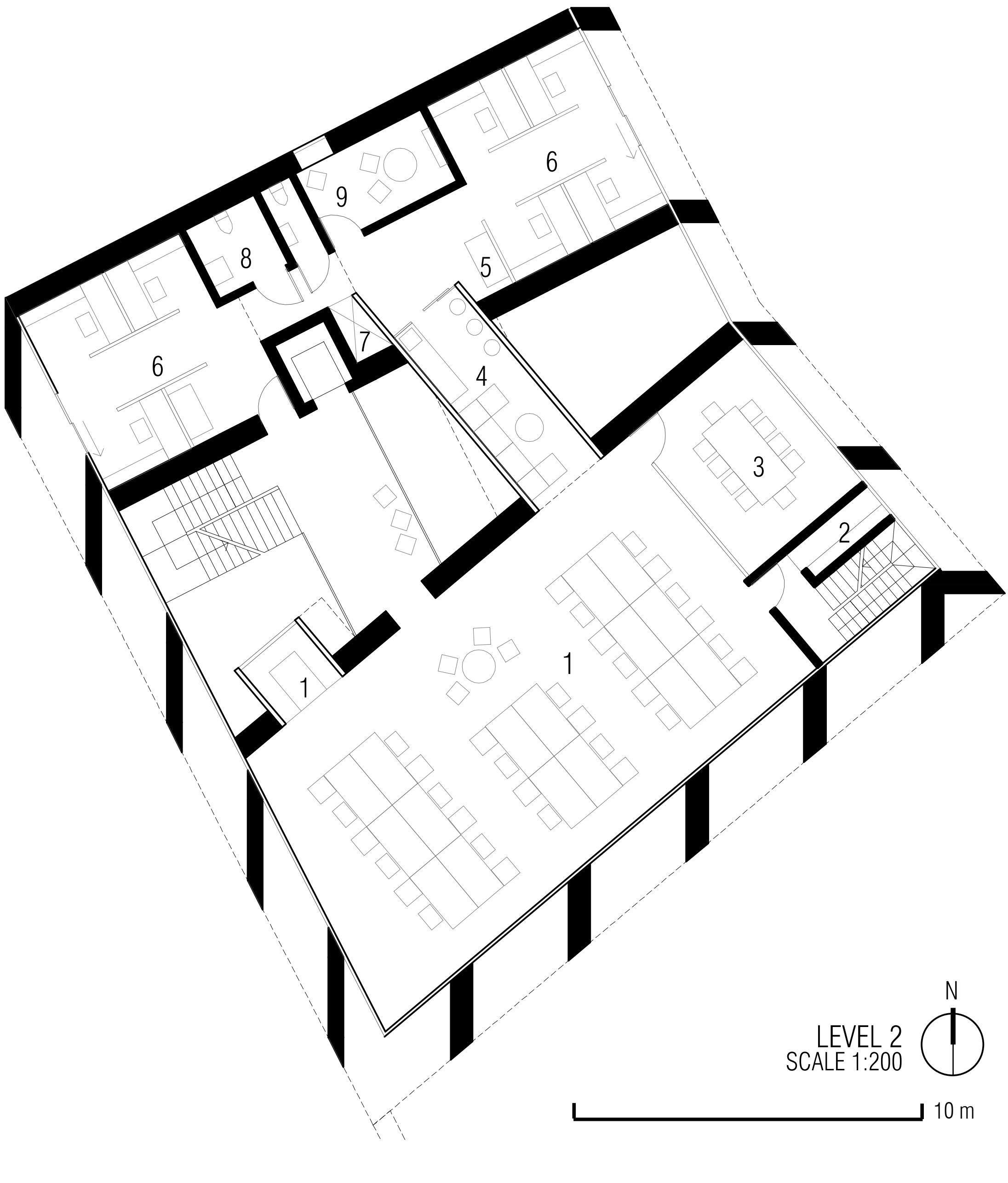
1. Main entrance (air lock)
2. Reception
3. Store
4. Mechanical room
5. Kitchen
6. WC/HWC
7. Janitors office

In the main entrance, the rammed earth walls that reach the roof dramatize the heaviness of the material. The space irradiates light to the floors and invites people to interact even between levels, it is a space where many things happen at the same time, like in a "street".

The heavy walls regulate the indoor temperature, the heat capacity of earth stores excess heat, which is the main problem in office buildings due to high loads of machines, people working and sun gains. The heat will be released when the office is empty and cooler during the nights,  in the morning the building won´t be so cold, requiring less energy to heat the indoor areas.

Proposal for the main entrance, heavy walls of rammed earth regulate the indoor temperature.





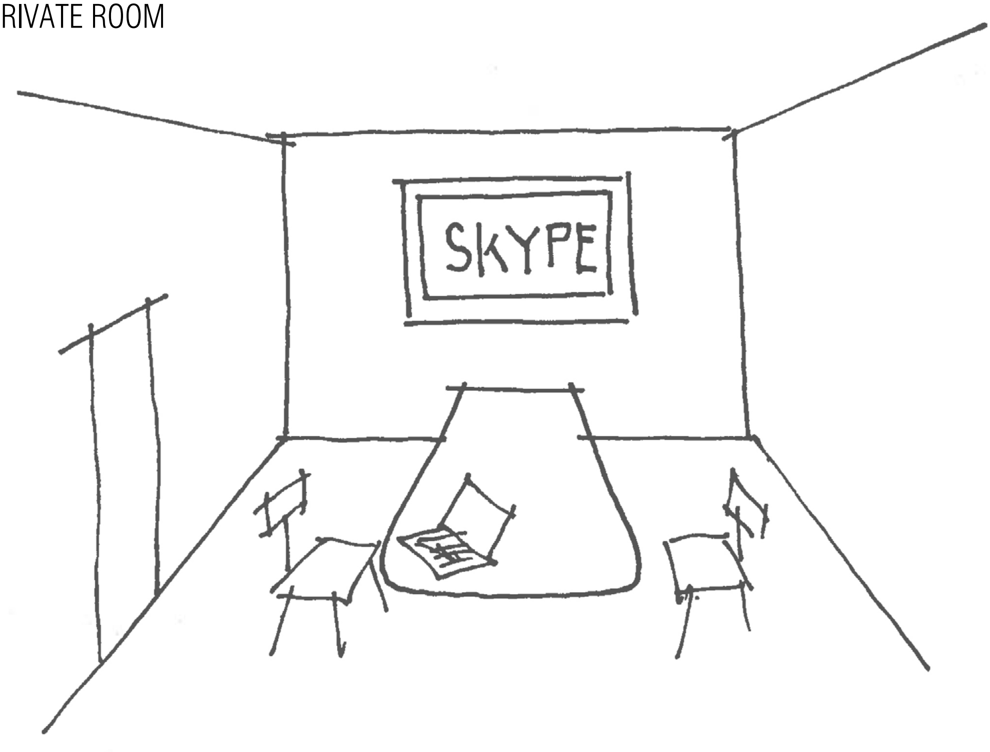

LEVEL 2
SCALE 1:200

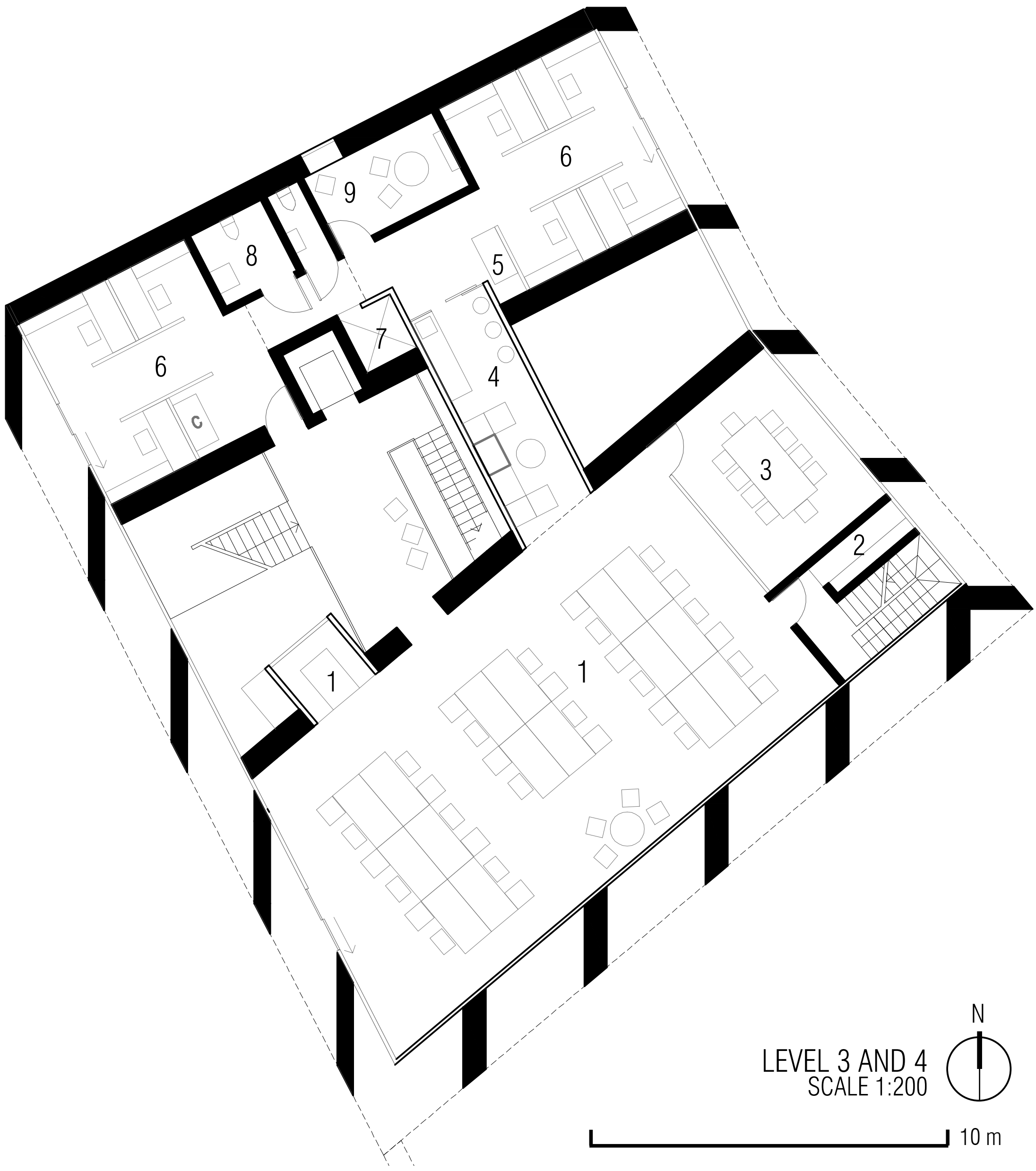
## LEVEL 2

1. Hot Desking
2. Storage room
3. Conference room
4. Fika room
5. Copy room
6. Individual modules
7. Ventilation rack
8. WC/HWC
9. Private room

The layout do not follows a hierarchical order, private rooms are not for senior managers. These rooms are places where people can participate in private meetings, individual or in group. Physical or on-line conversations could be performed with discresion in these type of areas.

## PRIVATE ROOM

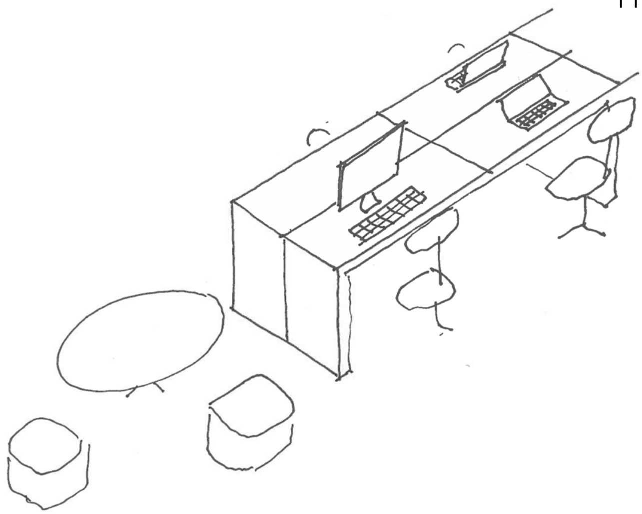




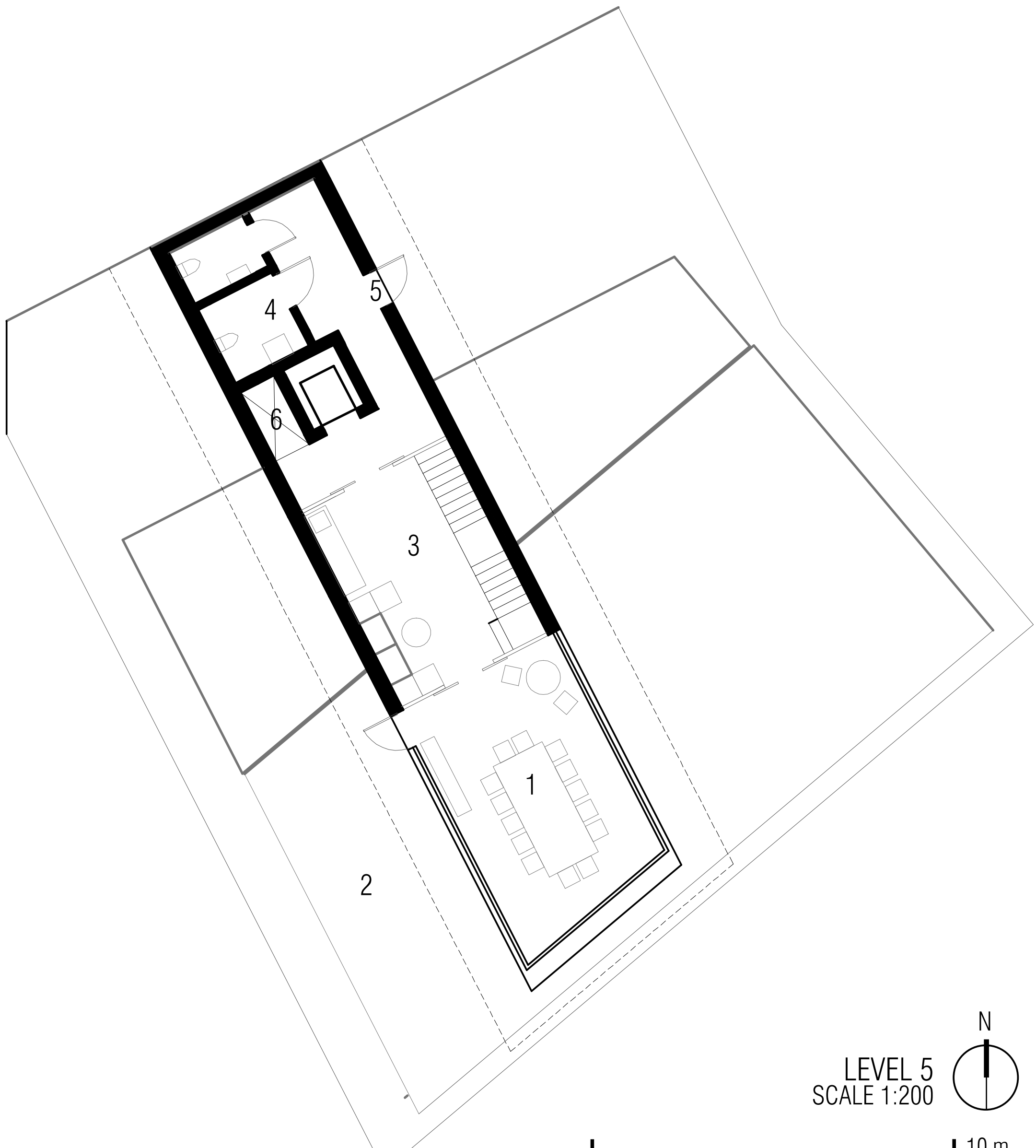

LEVEL 3 AND 4
SCALE 1:200

LEVEL 3 AND 4

1. Hot Desking
2. Storage room
3. Conference room
4. Fika room
5. Copy room
6. Individual modules
7. Ventilation rack
8. WC/HWC
9. Resting room



Hot Desking is a concept in office design where a mixture of big desks and couches takes place, allowing people to share information and exchange ideas. In the sofas people could have informal meetings without bothering the neighbouring desks. In this floor a resting room is proposed, but it could be used also as private room in other levels.

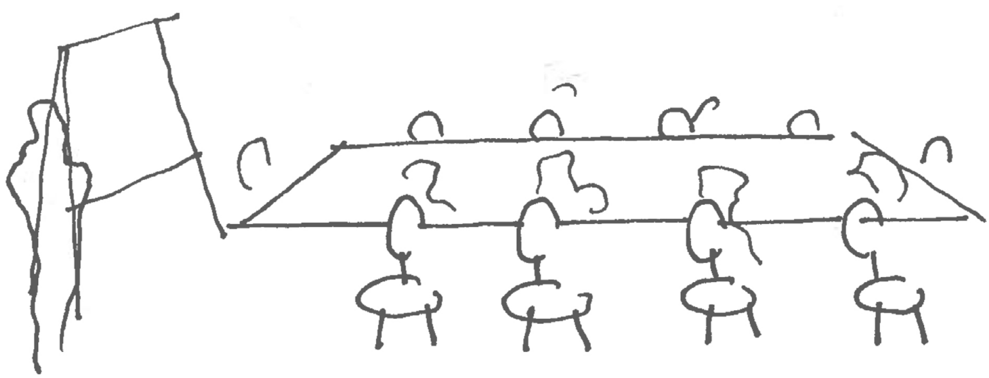



LEVEL 5
SCALE 1:200

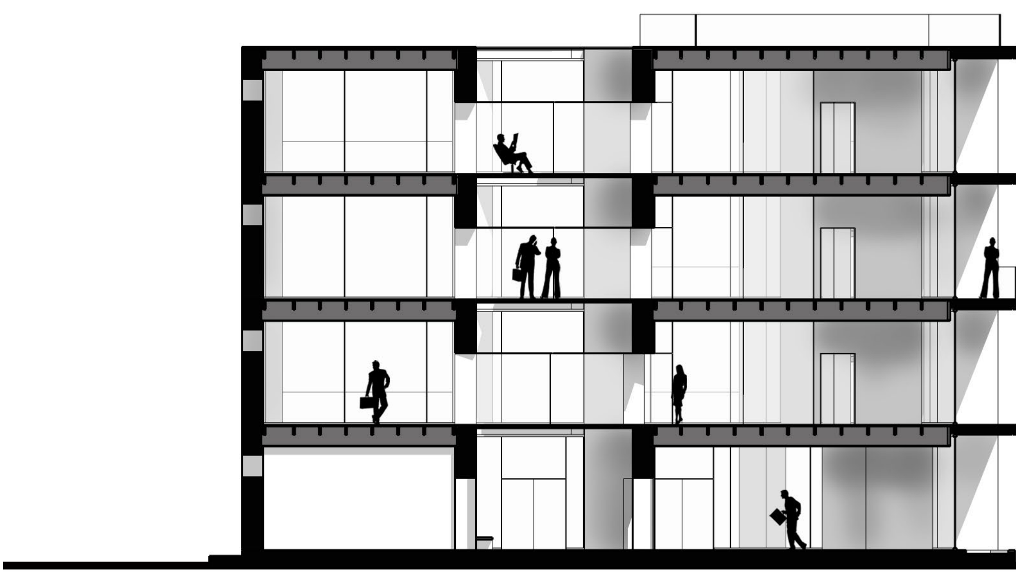
LEVEL 5

1. Booking room, for support or special meetings
2. Terrace
3. Fika room
4. WC/HWC
5. Access to ventilation machines
6. Ventilation rack

The final level is a long area that is destinated for workshops, client meetings or different activities that could be performed when the room is booked. There is also an access to the roof, where the ventilation machines would be placed. This ventilation part is still work in progress so I will not go into detail in that sense.



SOUTH ELEVATION
SCALE 1:100



SECTION
SCALE 1:100

# BUILDING CONCEPT

The building process presented in the next pages is a concept that can be improved in many ways. This is one example of implementation that can be used as future reference. The process is divided in three main groups: modules, weather protection and insulation. During description I will go back and forward into the analysis part to understand why did I choose a particular solution.

## MODULES

Building with earth in industrialized countries is still undeveloped. A good starting point would be to know if we count with the raw materials to build with this technique.

Lyckholms was choosed because is a urban area. One of the samples I analysed (see page 57) is from the area of Gothenburg, the analysed soil was suitable to build, in strength and workability.

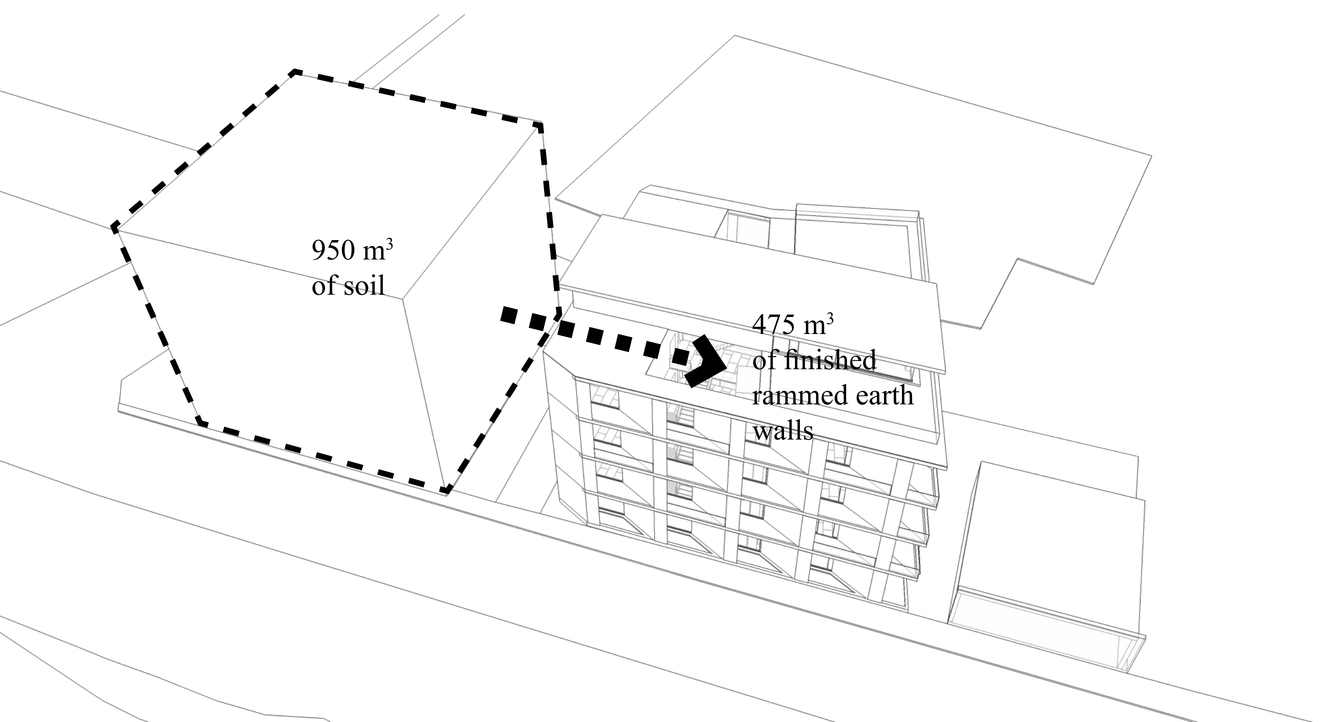
We can assume that the area of Lyckholms can provide the resources to build with rammed earth.

In march of this year an article in GP stated that the building of Marieholmstunneln in 2014 will make 500 000 cubic meters of prime clay, I quote in Swedish what Anna Liljemalm mentions in her article *Lera i överflöd vid nästa tunnelbygge:*

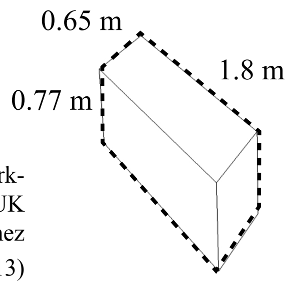
*I sex års tid med start 2014 kommer det att finnas lera i mängder att tillgå i Göteborg. När Marieholmstunneln tar form måste cirka 500 000 kubikmeter lera ta vägen någonstans.*

My proposal is to use the soil from the site as much as possible, but earth import from nearby areas is difficult to be avoided. The ammount of earth needed for the office is around 950 cubic meters of earth, compared to the works in Marieholmstunnel, the building needs less than 1% of the soil that will be excavated for the tunnel.

In volume 950 cubic meters is almost the size of the building proposal (around 20 meters height), this does not mean that we need all that amount of soil at once. The building concept consider a temporary workshop that allows two things: to produce rammed earth modules, and to store earth in the same site.

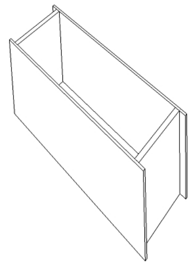


Like in the building process showed in page, we will first calculate the earth required for the modules. A module I found practical to build is 1.80 m long and 77 cm height. The height is enough for a person to ram standing out of the formwork. In the workshop I attended last april (see appendix A), we made a section of a wall with similar dimensions, thiner than the proposed modules.

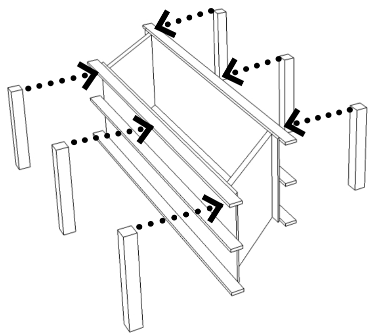



= 2 m$^3$
(4 cubic meters of soil per module)

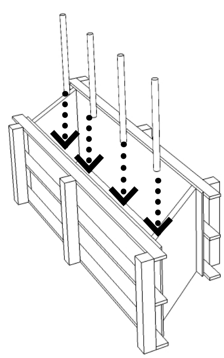
Rammed earth workshop in Norfolks, UK (David Martínez Escobar 2013)



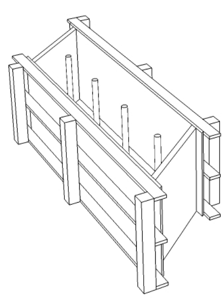
FRONTIERS
1” thick wood



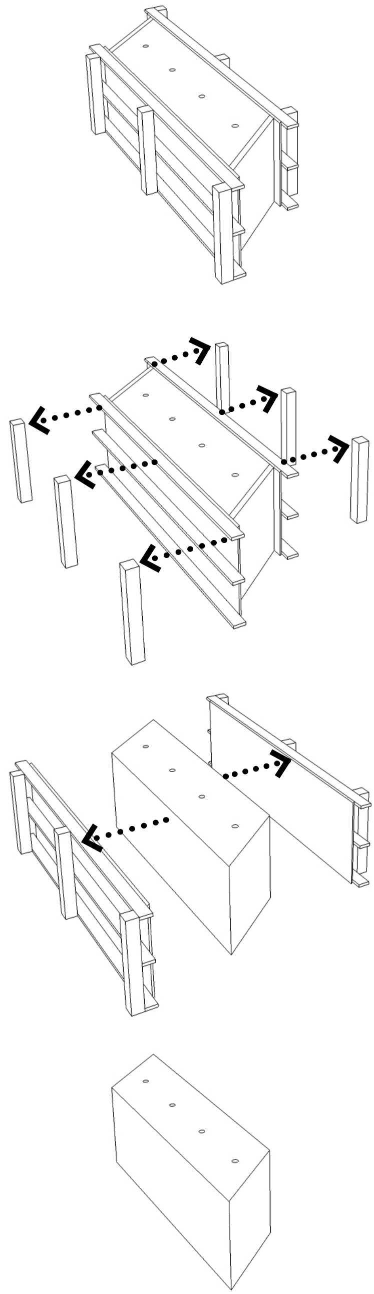
SUPPORTS
4” x  1” wooden ribs
2” x 4” wood verticals



PLASTIC PIPES
It is not necessary to add reinforcement in thick rammed earth walls (if the zone is non-prone to earthquakes). It is considered a bamboo reinforcement just as an example of implementation. 2” diameter pipes are placed before ramming.



MOULD
The formwork and the pipes are ready to receive the mixture.



RAMMING

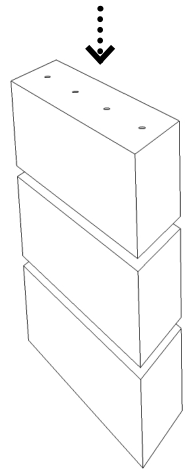
The module is rammed in layers of 7cm. In the NorfolksWorkshop it took about 4 hours to ram a similar module. We did not use mechanical tools.

FORMWORK

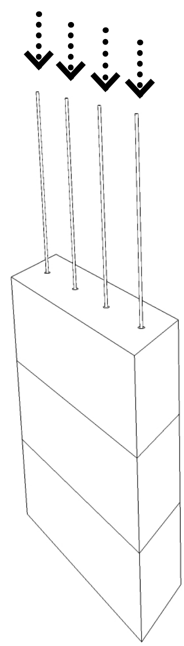
Formwork is removed after compacting.

MODULE

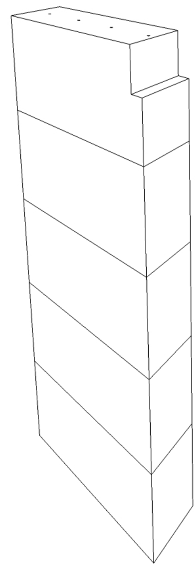
The module is ready to be stacked. Important to mention is that all the rammed earth elements in the proposal do not use any type of stabilizer.



STACKING
The modules are stacked one above each other. Since each module weights around 4 Tons the use of crane is necessary when assembling.

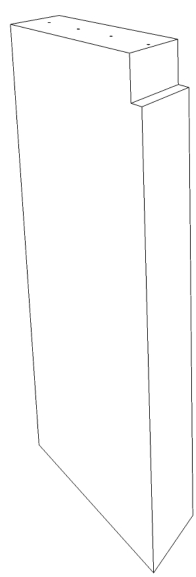


REINFORCEMENT
After certain height, bamboo of 20mm diameter is inserted in the plastic wholes (this process is just conceptual since no calculation about strength was done)



MORTAR

The wholes and joints are filled with earth mortar, we can see an example of this process in Martin Rauch´s project of Piazza Pintgia (see page 90).

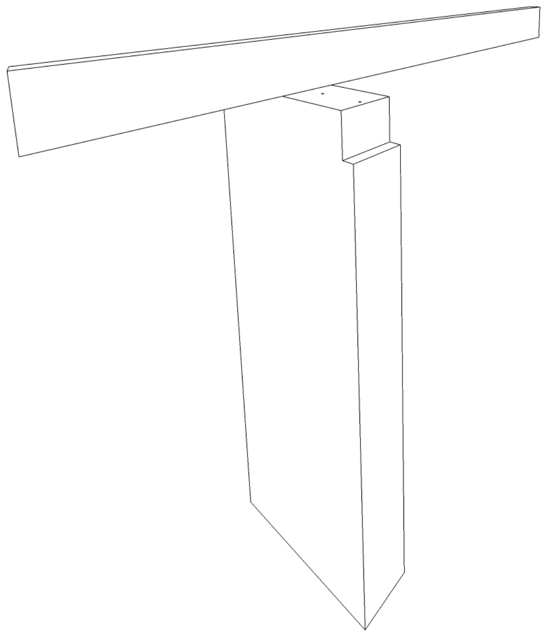


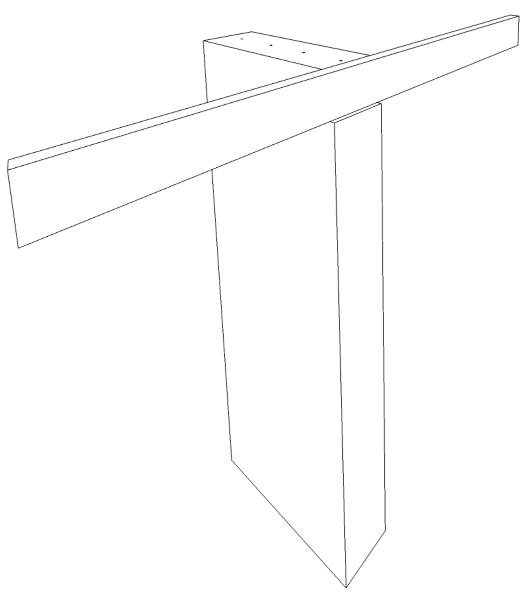
COLUMNS

With this process most of the rammed earth elements can be built.

There is an exception in the northern wall, since it will be insulated, the elements in this wall should be built differently.

The foundations for the building are proposed as concrete foundations. As we described in part 2 rammed earth elements should be protected in ground and roof from moisture.





## WOOD STRUCTURE

The rammed earth elements will support a wooden structure.

This wooden structure consists of glued laminated beams (see page 140), the structure was calculated by Andrea Mossielo, a Masters Student in Civil Engineering at Chalmers.

The program used was MathCad. Since the focus of this concept is not on wood there is no need for further analysis than the rough calculation showed in the Appendix D.

The calculation proposed 4Mpa for the strength of the walls, and it showed that the walls are using 50% of the strength capacity, which means that more floors can be added in the future.

## WEATHER PROTECTION

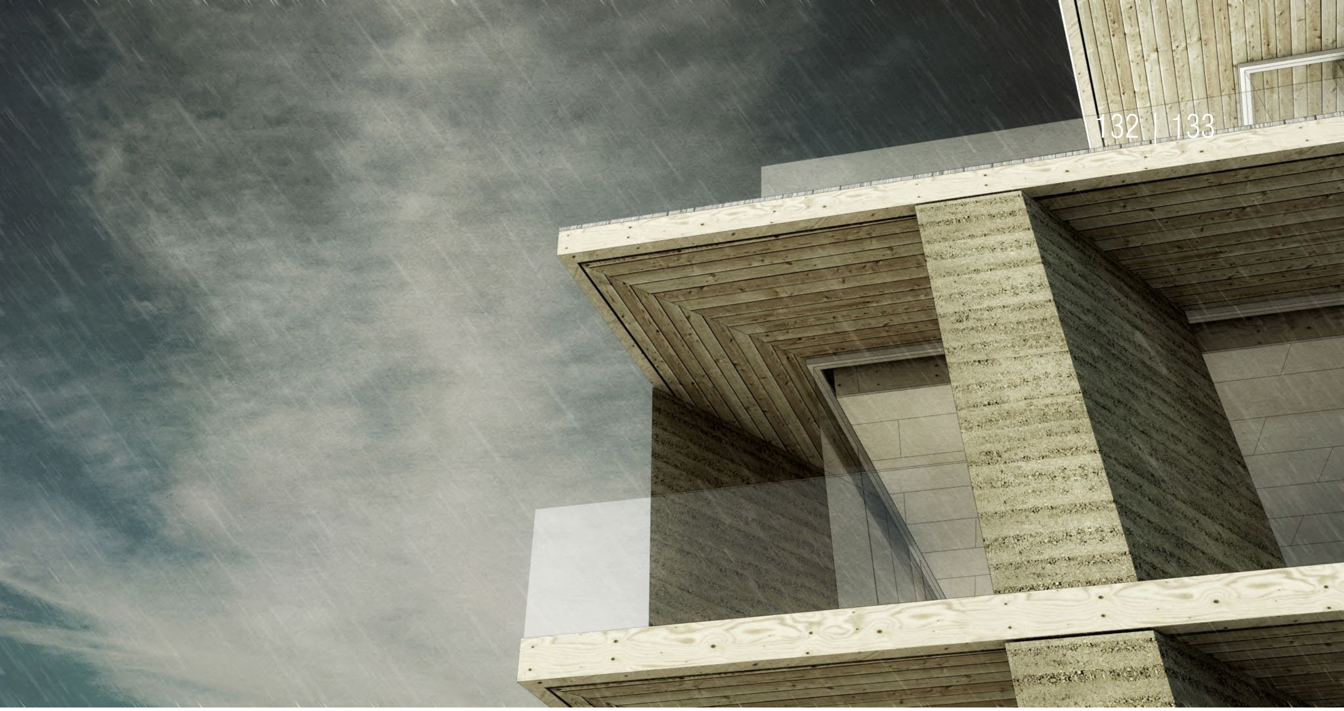
Rammed earth is not moisture or frost proof and the resistance of rammed earth to the effects of moisture varies considerably. (Röhlen, Ziegert 2011)

By this statement the rammed earth elements in the proposal will count with a wooden roof, protecting the walls from direct rain.

On the other hand, it is interesting to point out observations about rain. In the workshop that Ulf Henningsson and earthLAB organized last april (Appendix A), 30 rammed earth cubes were produced. Without curing the cubes, they were left exposed to rain for almost two months. Today (picture below) the cubes are almost intact.

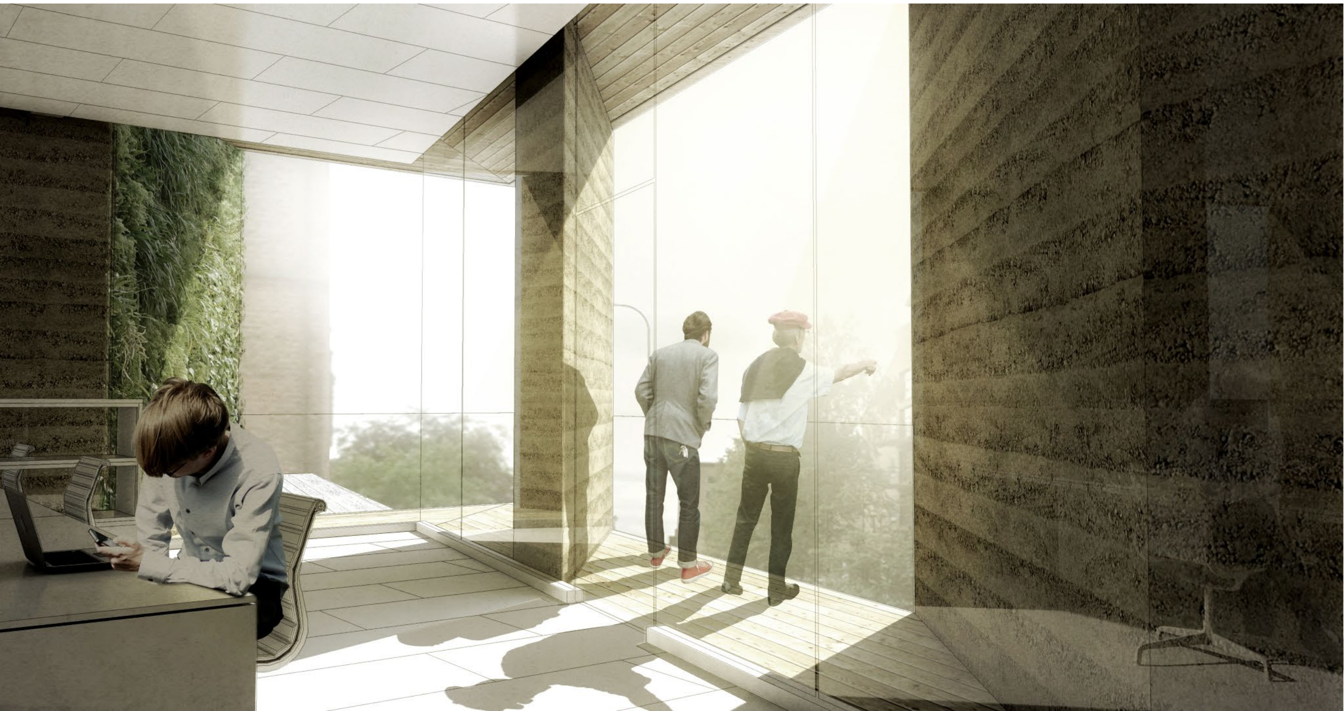
An aspect affecting the buildings performance is sun protection, mainly in the west facade. The rammed earth elements, protected by the roof, will screen the sun from the west. In office spaces where people and machines heat increase indoor temperatures, shading is crucial for thermal comfort.

Cube exposed to rain for almost two months without any type of stabilizer or protection. (David Martínez Escobar 2013)



The rammed earth columns are protected byt the wooden roof. These columns are loadbearing in the south facade, but they also provide shade to the interior spaces. In the west facade they are not structural, but they provide sun protection and create balconies.

Proposal for rain protection and sun shading.



## INSULATION

Most of the rammed earth walls are not insulated, the columns are placed outside the window frames. These walls have a U-value of 1.1 W/m$^2$K. Cold bridges are expected where the walls meet the wooden beams.

The inside walls are not insulated but the heat capacity will help to regulate the indoor temperature (see page 136).

The rammed earth walls with a U-value of 0.30 W/m$^2$K will be composite elements of 30 cm earth and 14 cm thick cork insulation, the thermal conductivity of cork as insulation is ($\lambda$) 0.04 W/mK.

The process used to build this walls, which correspond only 20% of the total built walls, is similar to the one described in part 6 (see page 96)

The windows are designed to have 20% direct sunlight in the summer (maximum), during the winter 80% of direct sunlight is alowed to hit the windows. It is considered to use windows with a U-value of 0.7 W/m$^2$K

# ENERGY CONCEPT

When talking about energy efficiency in buildings, one of the first things to think about is insulation. As we mentioned in part 5, rammed earth has a U-value of 1.1 $W/m^2K$ if its not insulated, this value is high in order to build according to regulations.

On the other hand, rammed earth has a high heat capacity, which means that the material will work as a sink. Some of the benefits of designing with thermal mass are:

-Improved ventilation and air quality
-Optimal decrement delay for reducing heat gains in summer
-Thermal comfort and reduced risk of overheating

Materials that provide a convenient level of thermal mass, usually gather three basic characteristics:
1. High specific heat capacity: the heat stored into every kg is maximised.
2. High density: the heavier the material, the more heat it can store.
3. Moderate thermal conductivity: the rate heat flows in and out of the material is close to the daily heating and cooling cycle of the building.

Rammed earth combines a high heat capacity, high density and moderate thermal conductivity. This means that heat moves between the material's surface and its interior at a rate that matches the daily heating and cooling cycle of buildings. (De Saulles 2012).

Rammed earth could have a low insulation value in buildings that are empty most time of the day, like houses. In office spaces the heat capacity could be a positive property of the material. For more information about rammed earth characteristics, and the comparison to other building materials see page.

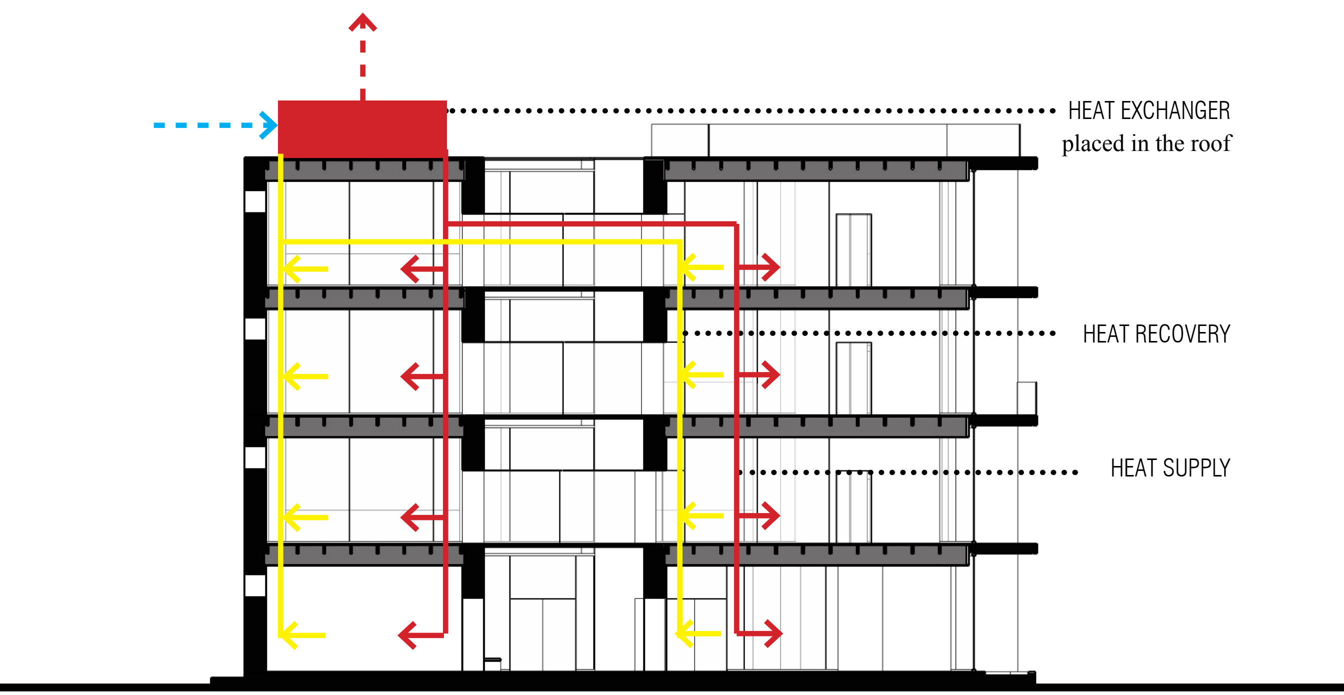
In office spaces, it takes more energy to cool the building than to heat it. This condition in buildings happens also in cold climates. Since the heat loads are high, people working, machines operating, sunlight, the buildigs are easily overheated.

Four scenarios were made for RE-Office: winter, spring, july (summer) and autumn. I will describe the most crucial ones, the building performance during the summer and during the winter in Gothenburg.

The concepts described in the next pages are not simulations, are state studies to roughly appreciate the bulidngs performance in different seasons. The studies were made with the support of my supervisor, John Helmfridsson.

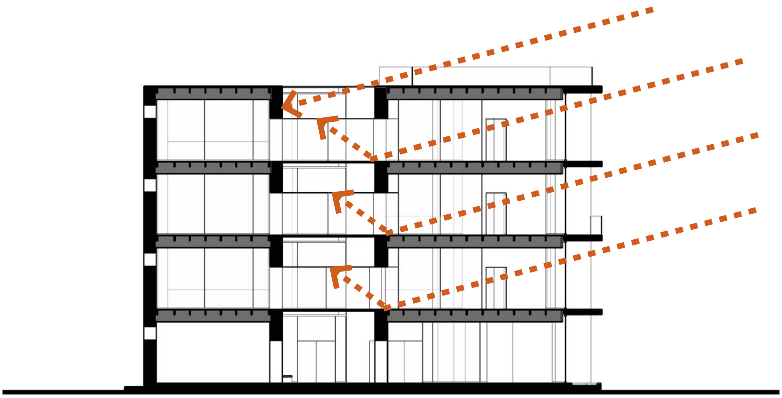
## WINTER

The proposal is to use a standard ventilation, heat exchanger. According to previous considerations we would have an energy consumption of 19 $kWh/m^2$ during the winter in Gothenburg.



During the heating periods, the low angle of the sun enter through the south facing windows, the heat is absorbed by the walls and released when the building is cooler.

During the night, windows shut and curtains drop could prevent heat loss. During the mornings the heavy walls would have released all of its heat, and the use of energy supply would be needed.



Facade proposal, winter time

## SUMMER

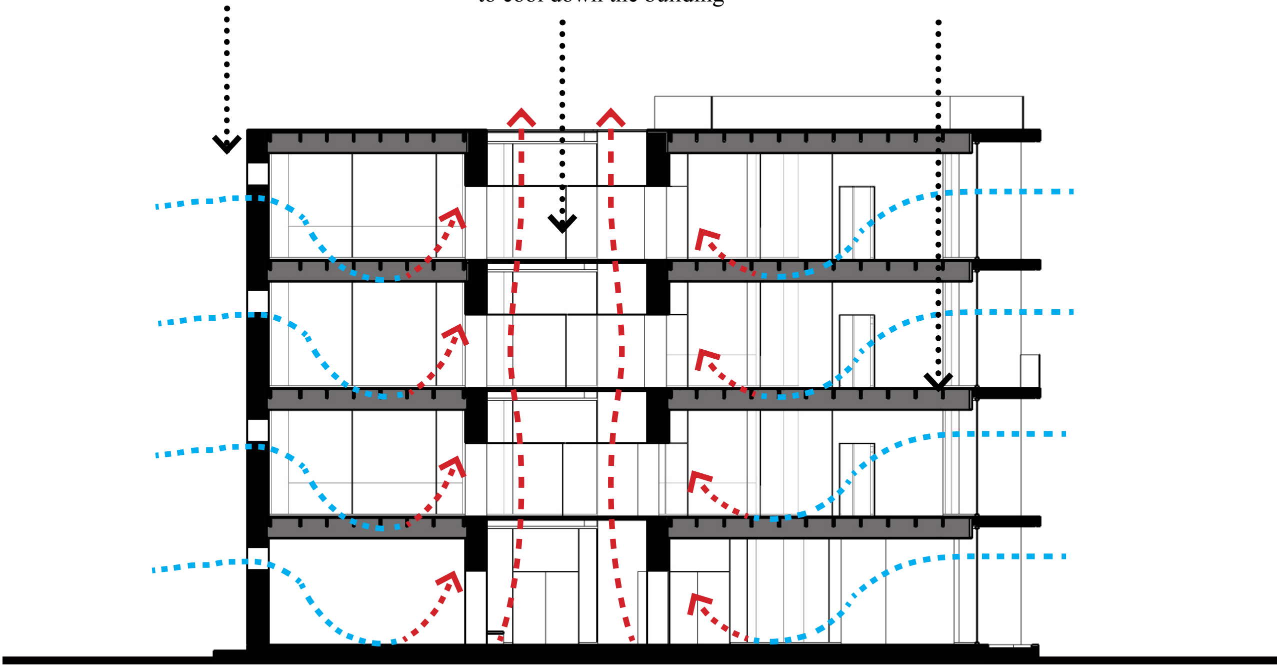
The concept during the summer is a night ventilation system that purge the excess heat in the walls. A company in Sweden that works with natural ventilation and digitally controlled windows is DELTAte.

( © 2013 deltate.se)

AUTOMATIC WINDOWS
digitally controlled windows open during night, the night air cools down the internal space

VENTILATION
heat is released in the center and top of the building, opening the glass roof during the night to cool down the building

THERMAL MASS
heat from day activities and stored in the rammed earth walls is removed by the cool night air



During the day, the overhanging roof in the south facade protects the inner spaces from the high angle of the sun. The windows are kept close to keep out the warm air. During the night the windows are opened to ventilate the building and cool the walls.

These overhaning roofs combined with the rammed earth structure create shades to the glazing facade, but also balconies where people could have work breaks, during summer alternative ornaments such as vertical greenery could work in the rammed earth walls

Using the thermal mass of rammed earth during the summer control indoor temperatures, but it also provides an optimal air quality, since earth can absorb humidity present in the air and enhences moist control.

Facade proposal, summer time

# STRUCTURE

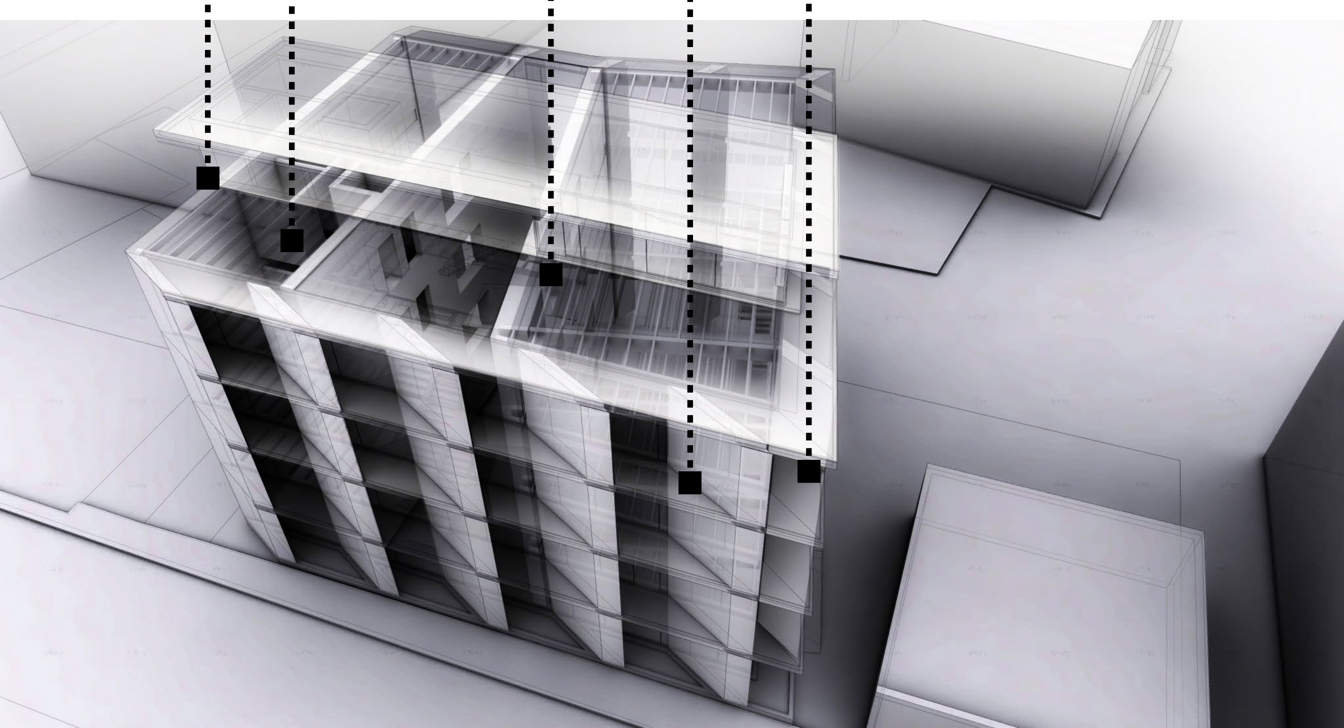
NORTH FACADE
Insulated rammed earth elements

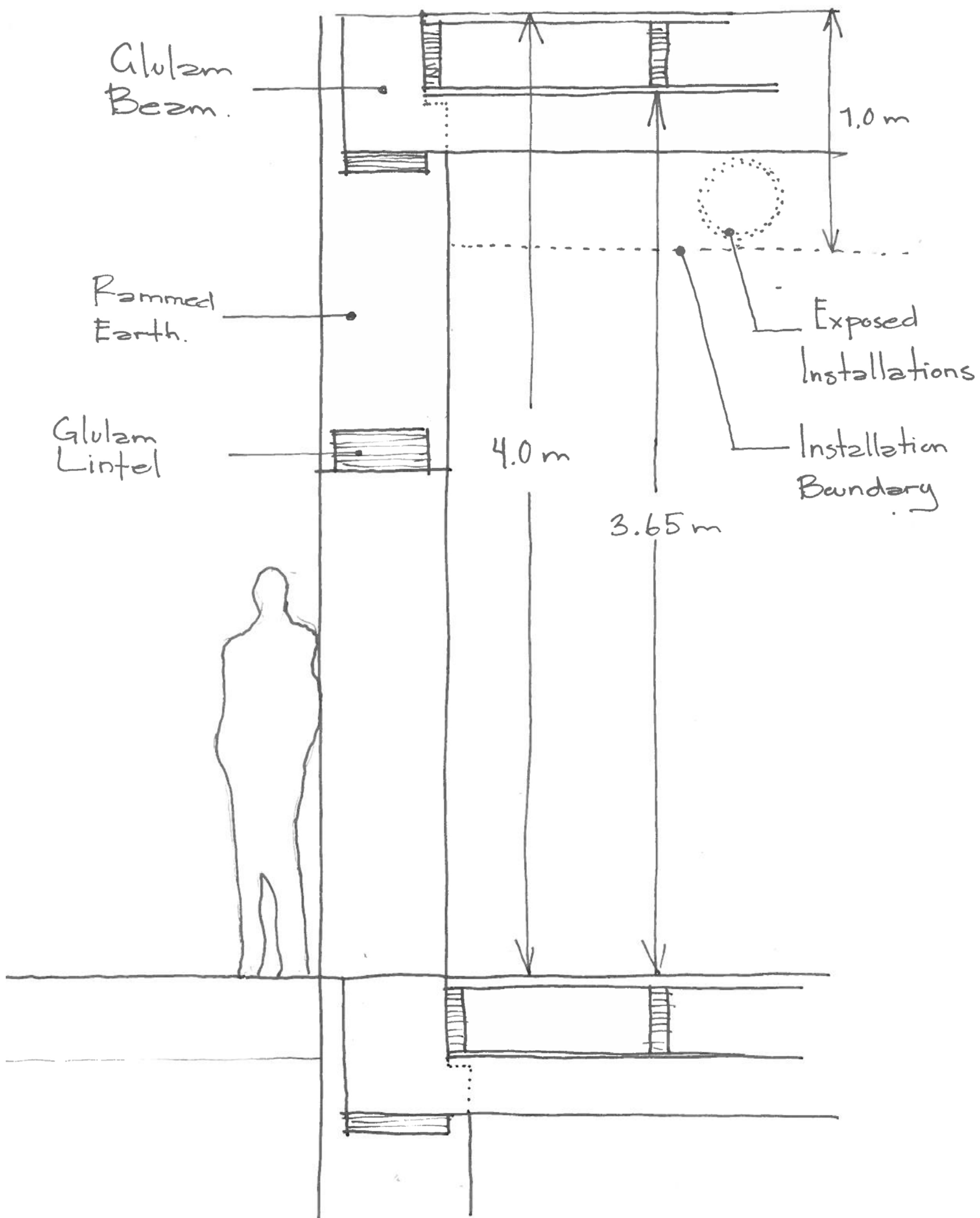
INTERIOR WALLS
Rammed earth, loadbearing walls

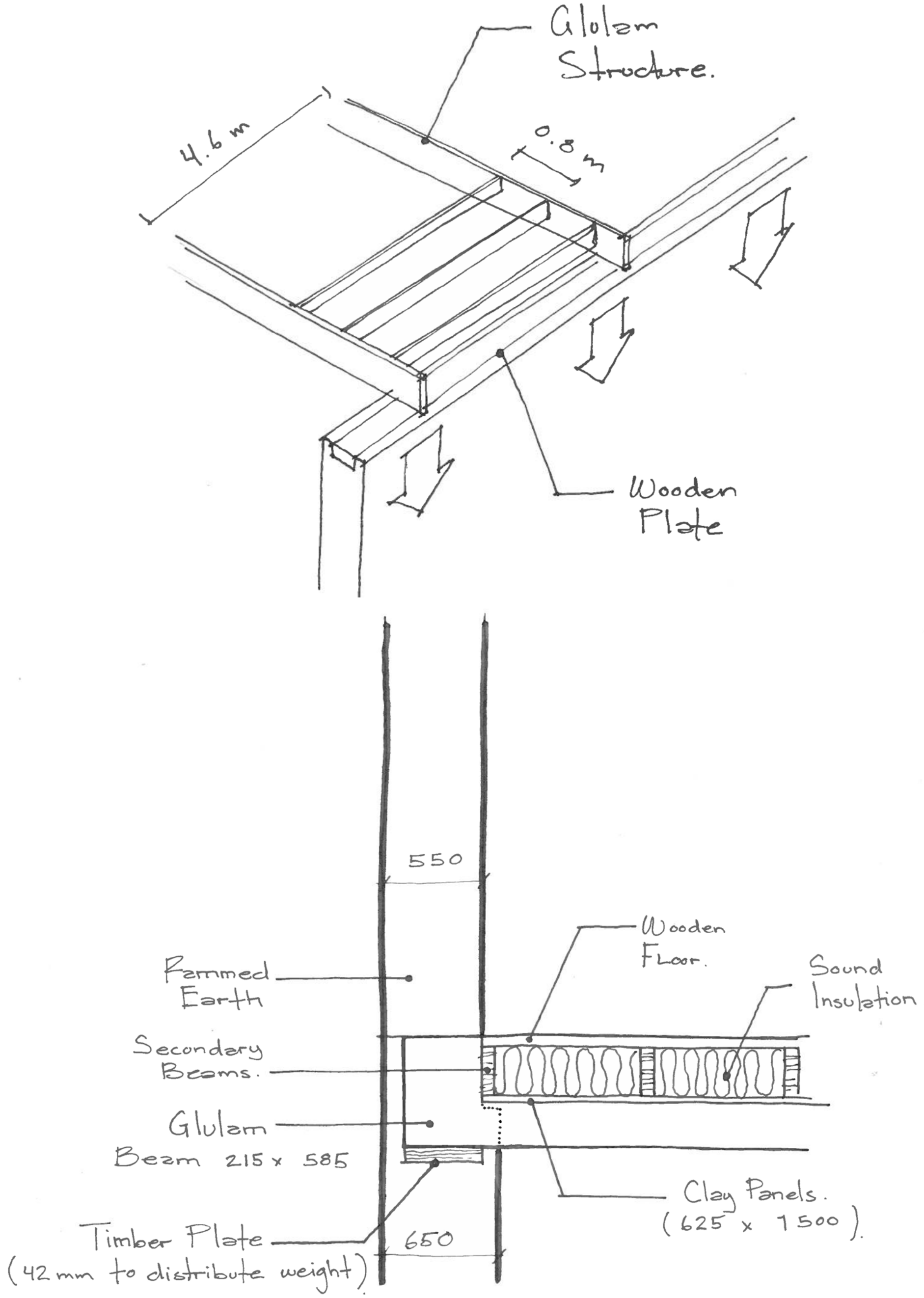
WEST FACADE
Prefabricated rammed earth modules, sun protection elements

FLOORING AND ROOFING
Glued laminated structure

SOUTH FACADE
Prefabricated rammed earth modules, loadbearing structure




Glulam Beam.
1,0 m
Rammed Earth.
Exposed Installations.
Glulam Lintel
4.0 m
Installation Boundary
3.65 m


Glulam Structure.
4.6 m
0.8 m
Wooden Plate
550
Wooden Floor.
Sound Insulation.
Rammed Earth
Secondary Beams.
Glulam Beam 215 x 585
Timber Plate (42 mm to distribute weight)
650
Clay Panels. (625 x 1500)

(part 8)

# DISCUSSION

# RAMMED EARTH IN AN URBAN CONTEXT

The question about building with non-traditional techniques in industrialized countries could lead to many directions. There are different aspects to analyse, and many factors to comprehend.

I have been describing that rammed earth is a non-traditional technique is Sweden. This assumption generated certain reactions during the last seminar in may. There have been examples of rammed earth and rammed lime in Sweden since the begining of the 1900s, according to Lars-Allan Palmgren.

Annika Ekblom in her thesis work *Om Hus av Jord och Lerhalm*, describes houses in Sweden that are built entirely with rammed earth. Some of those houses were built in the 1940s.

There is also a strong tradition of building with clay. Lena Falkheden, Ulf Henningsson, and many others are experts in building with natural materials. Clay and its properties are widely known in Sweden. Nevertheless, rammed earth is a technique that few persons are familiar with.

Strawbale house, study visit with Lena Falkheden, Bottna, Sweden (David Martínez Escobar 2012)

When I mention that earth is a non-traditional method in Sweden, I am not implying that there is no knowledge about it, but I believe there is a lack of practice. When talking with classmates, friends, or even teachers about rammed earth, the topic seems to be new, sometimes exciting, sometimes misinterpreted.

My general assumption is that there is no tradition in this particular technique, in rammed earth; in comparison to wood, concrete, steel, or even other natural materials like straw or wattle and daub, which are easily recognized.

My reflection is also fundamented in the buildings that we see in the city, and what is the “usual thing to do”. Because of this I raise the question about incorporating rammed earth, as non-traditional technique, in urban areas.

An experience that reinforced my thought about the absense of rammed earth projects in Sweden was during last july, when we held a workshop in Gothenburg to teach rammed earth.

## JORDSTAD - JULY 2013

During the spring 2013, a group was created by three organizations: Byggbrigaden, Stadsjord and earthLAB (see Appendix A). The name of the group is Jordstad ("the city of earth" in English).

The idea behind this project was to create meeting places, to teach rammed earth as building method and to promote urban agriculture. We selected two different sites to work with, both in Hisingen, more information can be found at www.jordstad.se.

The design consists of walls that create a small microclimate. Walls that work as sitting places but also hold a small green house.

The first challenge to overcome was to find the material to build with. In many cases the earth you dig from a site can be used to build (page 57). In Hisingen we found mainly pure clay. This was a complication since we wanted to use a local material, but the import of aggregates was necessary.

These small structures of soil are probably the first ones in the urban area of Gothenburg, in the end the walls were covered with linsed oil to protect them from direct rain.

Rammed earth wall proposal at Fyrklövern (David Martínez Escobar 2013)

A message was sent to the people living in those neighbourhoods, a message about building with earth. The reaction was different from person to person, but many of the questions while building was if the material used was concrete, since the appearance was similar.

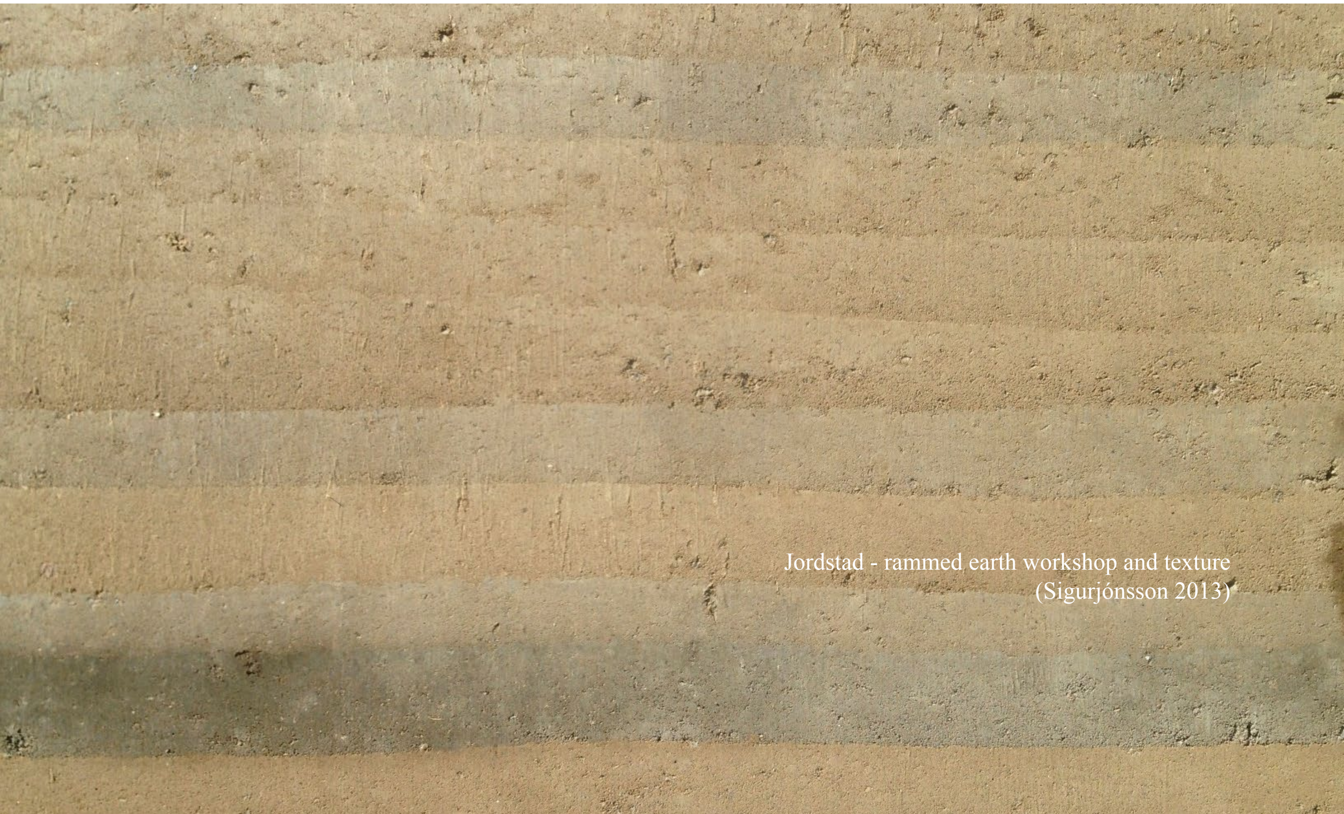
In my opinion, rammed earth has a bright future if we find a way to industrialize soil, thinking in pre-fabrication at the same time.

The traditional method is intense, we have to admit, it will never compete with the way of building today. It is a beautiful technique, the heavy work is rewarded everytime you take away the formwork and see the fresh layers as a natural stratification.

My vision is to stop thinking in rammed earth as a do-it-yourself technique, and start to use it in our cities. Educate persons, not only those interested in natural materials, but also those less attracted by alternative methods: builders, planners, those who are shaping our cities today.

I like to compare the building process between concrete and rammed earth. They are more similar than we think, both materials are composed by a mixture of a “glue” material (clay or cement) and aggregates (sand and gravel).

Perhaps rammed earth will never be as used as concrete, but the idea of this booklet is to inspire people to analyse when and how can earth be used, in combination with commonly used techniques.



Jordstad - rammed earth workshop and texture
(Sigurjónsson 2013)

In rammed earth as in concrete, formwork is a big component of the building process, they can be done from metal or wood, and it takes more time to prepare the forms than to ram earth or to pour concrete.

In terms of built elements, both materials are heavy, with a robust character. They get stronger and stronger as they dry. Both techniques demand skill, knowledge and passion.

Costs in rammed earth works are higher than average concrete methods, around 10% more. One of the causes might be that people is not familiar with rammed earth, there is no demand. Another important factor is that labor is expensive in industrialized countries.

This could become positive if we think that we are paying for a method (work), and not for a material (resource). One could argue that rammed earth is expensive because it takes time to build, but in the long term perspective, it generates so many benefits: thermal comfort, indoor air quality, re-use of natural materials, low-energy demands when constructing.

In developing countries rammed earth or similar techniques are viable. Today, rammed earth in industrialized countries is cheap as a do-it-your-self technique, the material is almost free and with help of volunteers a building can be really affordable.

Is it reasonable to pay more for rammed earth? I would like to think that this thesis serves as inspiration to  discover possibilities, finding solutions instead of problems. This could be an opportunity for a material that is abundant, local and almost for free.

I would like this thesis to be considered also as a question for the the building industry, is that all we have? There is the possibility to build in a more sustainable way, without compromising design and safety issues. The impact of investing in these methods, go beyond the inmediate region.

If people in Germany could build tall rammed earth houses in 1850 (see page 160), I am positive that today, with all the technology in the building sector, and all the information that is available, we can improve those traditions.

It is also interesting to raise the question about building regulations. We know that Swedish regulations are strict, according to Fleming Norrgren who planned the houses in Steninge (see case studies), it is not possible to build houses wth rammed earth in Sweden anymore. Is it possible to build other typology of buildings?

## COCNLUSSIONS

When talking about earth building techniques:
-Earth is one of the most used building materials around the world
-Earth is natural and always reusable
-Earth saves costs in material and transportation
-Earth is an honest material
-Earth does not require a high demand of energy to produce it
-Earth can be loadbearing
-Earth has a strong architectonic expression

Some limitations of earth buildings are:
-Earth is not frost or water proof
-Earth is not standardized
-Earth is labor intense
-Earth buildings can be more expensive than traditional building techniques, under certain contexts

One should not forget the architectural qualities of earthen materials, (see page 73). Earth is a material used in offices, houses, comercil buildings, public buildings; with the wave of interest in sustainable constructions we should not leave aside techniques like rammed earth.

# CASE STUDIES

# STAMPAT JORDHUS

STENINGE, SWEDEN

Building period: 2007

The Mäkinen family moved to this earth house in 2008. The house is part of an interrupted plan of building five similar houses of rammed earth. Only three of them were built.

Regulations of building construction in Sweden did not allow to finish the other projects. “These are the last houses in Sweden built with this technique”, explains Flemming Norrgren in an article for Göteborgs Posten. According to the norm, the low insulation value of this material increases the energy required to heat the houses.

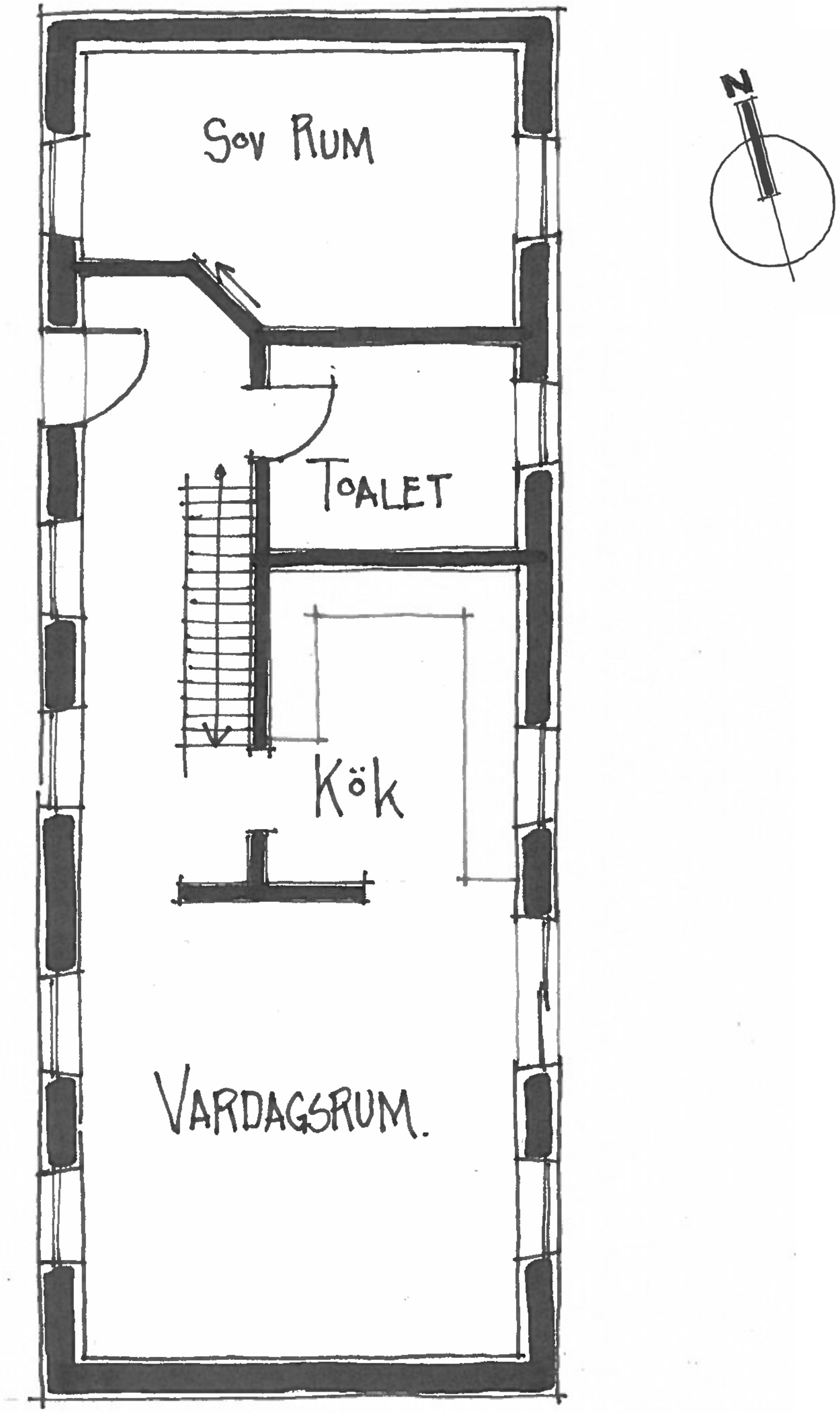
Rammed earth house in Steninge, Sweden (David Martínez Escobar 2012)

The house was built with earth extracted from a nearby area. The walls are 50 cm thick and do not count with insulation. I had the opportunity to visit the house and talk to Göran Mäkinen, who does not feel the difference between his house and any other wooden construction he has lived in, in terms of thermal comfort.

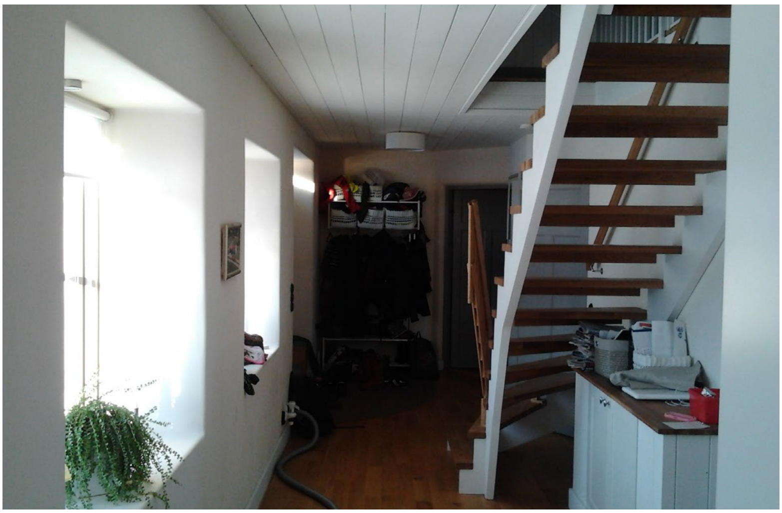
After constructed, the rammed earth walls were left exposed, without a plaster, during one entire year. This helped the walls to breathe, avoiding future cracks.

Göran is fascinated with the fact that it takes less time to heat the house every year, this could be, until a certain point, because each year the walls dry and less water is present in the rammed earth elements.

Photo of the house without clay plaster (Goran Mäkinen 2012)

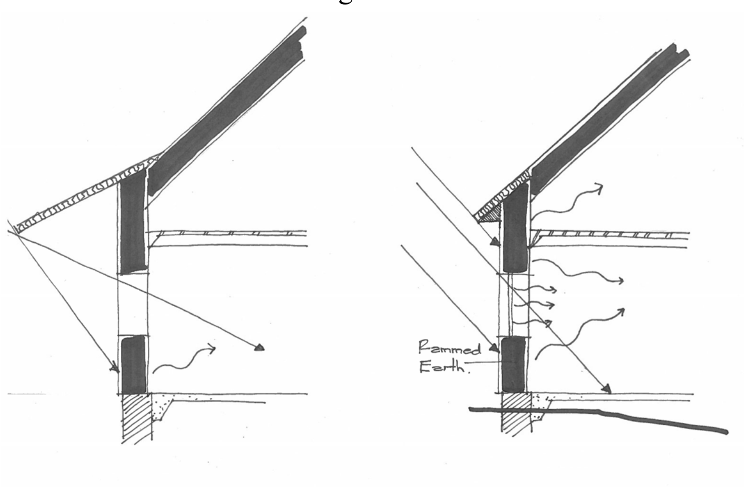

N
SOV RUM
TOALET
KÖK
VARDAGSRUM.

The house consist of a rectangular plan of 160 m$^2$ of construction area (previous page), oriented from South to North. It seems that the house works during the winter, but there is a problem during the summer. The west side of the house gets too warm. There are numerous openings in the west elevation that enhances heat flows, and the roof do not cover the sun during the peak hours.



Window openings to the west (David Martínez Escobar 2012)

The heavy walls can store heat and release it, so if they are exposed to the sunlight during the summer, the indoor temperature can increase considerably. A solution for this situation could be an overhanging roof that let the sun come in in the winter, but protects the windows and walls during the summer.



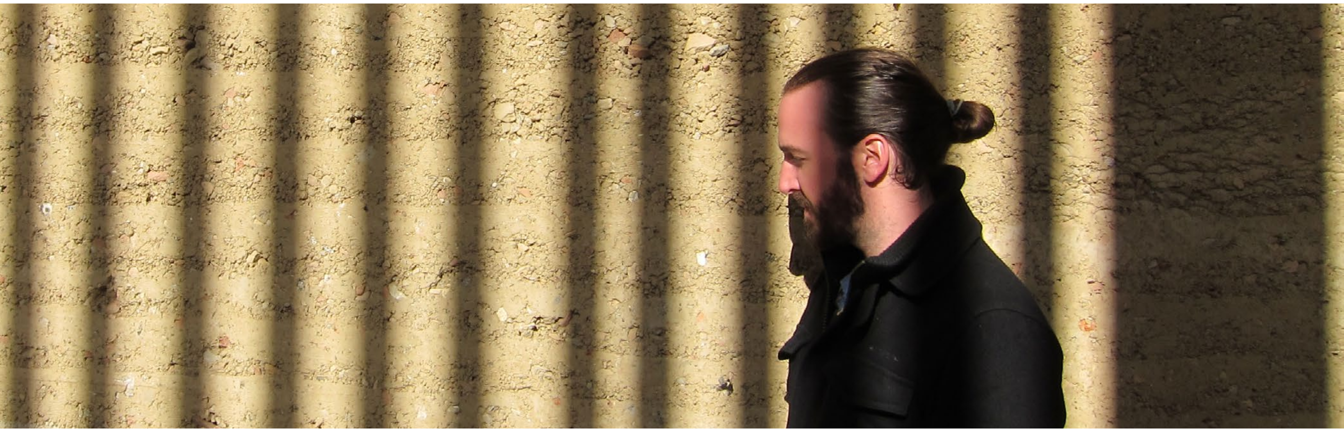
In terms of costs, explains Göran, the price of the houses was higher than those of average houses of the same dimensions. Even if the material cost is low, the labor cost can be expensive, since the method demands an intensive and meticulous work.

For Göran and his family it is not important to have the rammed earth walls as the final exposed layer. The entire house is covered with clay plaster, inside and outside. What attracts Göran is to know that his house is built with a local and ecological material.

Important to mention, during construction the time to build the rammed earth walls was only of 2 hr/$m^3$, this time is considerably short if we compare it with the time to build exposed rammed earth walls (see page 70). The reason for this decrease in time is due to the clay plaster that was planned to cover the walls, in exposed walls the time could be even three times longer.

East facade
(Martin von Brömssen, 2012 gp.se)

# THE CHAPEL OF RECONCILIATION



Texture of the walls in The Chapel of Reconciliation (David Martinez Escobar 2012)

BERLIN, GERMANY
Building period: 1999

The chapel is located on the site of the former Reconciliation Church, demolished in 1985 to clear the area between the walls dividing East and West Berlin. The chapel is elegant, sober, and serene.

The rammed earth wall contains large fragments of broken brick from the former church, as well as gravel, which together constitutes the 55% of the material. (Minke 2009)

The design belongs to Berlin architects Rudolf Reitermann and Peter Sassenroth, with the collaboration of Martin Rauch in the earth materiality. The architects had planned to use glass and concrete for the building, but the parishioners found that the concrete bore too strong a reminiscence to the hateful Wall. The parish suggested earth and wood instead of concrete and glass.

It is possible that many people visit the Chapel of Reconciliation without knowing that it was built ramming the earth from the same site. The photos on the next pages show the exterior of the church, the interior of the chapel, with the untreated rammed earth walls, and finally the space between the rammed earth and the wooden structure. A dynamic interaction between light and shadows evoques the visitor to walk around the chapel and be close to the walls.

The Chapel of Reconciliation (David Martinez Escobar 2012)

The Chapel of Reconciliation
(David Martinez Escobar 2012)

# HOUSE RATH

WEILBURG, GERMANY
Building period: 1850

Weilburg is famous for its tradition in buildings of rammed earth. The buildings are documented in the book *Der Pisé-Bau zu Weilburg an der Lahn* by Von Wilhelm Schick, published in 1987.

In October 2012 I made a trip to Weilburg with the purpose to find the tallest rammed earth building in Germany. Six floors of rammed earth in combination with a timber structure were built in the year 1850, according to the book *Der Pisé-Bau zu Weilburg an der Lahn* by Wilhelm Schick.

House Rath (David Martinez Escobar 2012)

Different data exists about the construction date of the building, Gernot Minke in his book *Earth Construction Handbook, The Building Material Earth in Modern Architecture* mentions that the house was built in 1828. (Minke 2000, p.14)

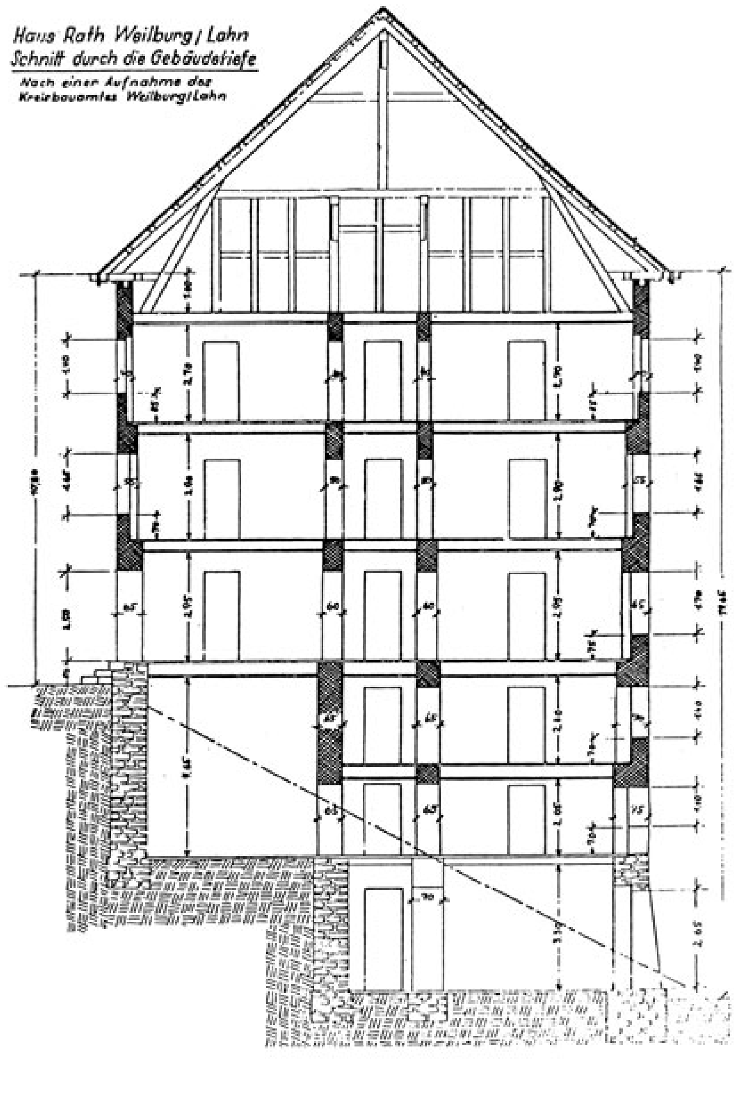
When I approached the house, I distinguished three layers, first was the rammed earth wall (1), then a clay plaster (2) reinforced with straw, and then a third layer of cement plaster (3); this means that the facade have been renovated several times.


Three layers of different plasters, House Rath (David Martinez Escobar 2012)

The building is in good condition. The plaster in the facade looks damaged, but the construction has been in this place for 160 years and is still used. This is the tallest rammed earth building in Germany and serves as an example that it is possible to build more than two story height buildings with this technique.

More rammed earth buildings exist in Weilburg, this tradition of building with pisé led to several houses that today stand still, in many cases the facades have been renovated.

The next drawing is a section of the building as shown in the book *Zur Geschichte des Lehmbaus in Deutschland*,  by Jochen Georg Güntzel and Okobuch Verlag in 1988. The wall begins with 750 mm thickness at the base and reduces by 90 mm each floor up, being the last one of 300 mm thick.



# BUILT EXAMPLES

# HOUSE RAUCH

SCHLINS, AUSTRIA

Building period: 2008

Martin Rauch is an artist that initiated working with ceramic compositions. With this sensitivity as ceramicist, Rauch re-configurated the expression of rammed earth as building material, to the point of maximizing all the qualities of the earthen material.

In his process, technical improvements evolved together with the architectural form. He analyzed and experimented with the natural composition of the materials, the compression methods and the shape of the formwork. Inspired by the old techniques, he developed the method using additional layers of reinforcement.

House Rauch
(Bühler, Rauch 2008)

House Rauch
(Bühler, Rauch 2008)

"it was fascinating that after millions of years this deep-sea floor first saw the light of day again in **the form** of my house"
(Martin Rauch)

The design of the house belongs to the architect Roger Boltshauser, in collaboration with Martin Rauch. The artists explored rammed earth as no one has done before. In this house located in Schlins, Austria, the only thing that is not earth are the windows and the sculptural metal railing in the stair. Roofs and floors were covered with tiles of fired clay obtained from the site itself.

The house is a three-storey building with 45 cm thick rammed earth walls, which are fully structural and built with extracted material from the site. The fired clay bricks in the facade function to protect the walls from erosion, slowing down the water running through the surface.

The house is an example that rammed earth can be performed meeting architectural qualities, showing that highly aesthetic demands can be achieved with ecological materials. The material responds directly to the physical situation of the house.

There is also a social responsibility behind this project. For the House Rauch great value was placed on the use of regional materials as well as on collaboration with craftsmen from the town and nearby areas. This is the house where Martin Rauch still lives with his family.

House Rauch
(Bühler, Rauch 2008)

# METEOR VINEYARDS

CALIFORNIA, USA

Building period: 2005

The house was designed by Cutler-Anderson Architects, using rammed earth walls in combination with timber structure. The firm has other projects featuring rammed earth elements, like the Bodega Residence showed on page 11 of this report.

In the United States a building code regulates that rammed earth elements should count with 5% of cement. This is different in Germany, for example, where rammed earth constructions do not have cement as stabilizer.

Meteor Vineyards
Cutler Anderson
Architects
(© 2013 Cutler
Anderson Architects)

Meteor Vineyards
Cutler Anderson
Architects
(© 2013 Cutler
Anderson Architects)

Meteor Vineyards
Cutler Anderson
Architects
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# GLOSSARY

**abrasion resistance -** a property which allows a material to resist wear

**adobe bricks -** handmade unbaked loam bricks. A sandy loam is mixed with water, cut straw is usually added, the loam is thrown into wooden moulds and let dry under the sun

**bitumen -** highly viscous, semi-solid form of petroleum, used in the past as stabilizer for earthen constructrions

**cement -** binder agent, mixed with sand and gravel creates concrete elements

**clay -** fine-grained soil with particles of diameters smaller than 0.002 mm

**clay plaster -** type of plaster composed of clay, sand and water, sometimes with aggregates such as straw to strengthen its composition

**cob -** a name given to one of the four basic earth-wall construction systems, in which walls are constructed by stacking up a sticky clay mixture without formwork or additional support

**cold joints -** the interface in a rammed earth or concrete wall, either vertical or horizontal, where work was halted and then commenced at a later time

**compressed loam bricks -** name given to loam bricks compressed with hand-operated or motorized hydraulic machines

**coligüe -** perennial bamboo native to the forests in Chile and Argenitna

**formwork -** a temporary construction intended to support and give shape to concrete or rammed earth during the placing and curing phases

**gravel -** grained soil with particles of diameters larger than 2 mm

**loam -** scientific term for earth when used as building material. It consists on a mixture of clay, silt (very fine sand), sand, and occasionally larger aggregates such as gravel or stones

**lime -** inorganic material used as building or engineering material, and also to stabilize earth elements

**pisé de terre -** french term for rammed earth

**sand -** fine-grained soil with particles of diameters between 0.06 and 2 mm

**silt -** fine-grained soil with particles of diameters between 0.002 and 0.06 mm

**u-value -** overall heat transfer coefficient that describes how well a building element conducts heat

# APPENDIX

# APPENDIX A - EARTHLAB

EarthLAB is a group formed in 2012 by students from Chalmers University of Technology. The idea of creating this spontaneous group is to spread the word about alternative building techniques and urban agriculture.

The group is formed by Ásgeir Sigurjonsson, Josua Smedberg, Shea Hagy and David Martínez. With different backgrounds but similar interests we have started an interisting collaboration not just in Chalmers, but also outside the student environment.

In march we went to a Rammed Earth Workshop In Norfolks, UK, organized by Michael Thompson, where we had the opportunity to meet more people interested in building with rammed earth.

We started a blog where people can follow what we have done. (http://earthlabchalmers.wordpress.com/)

Ásgeir Sigurjonsson, Shea Hagy and David Martínez in the Rammed Earth Workshop, Norfolks, UK.

In April earthLAB organized a rammed earth workshop together with Ulf Henningsson, around 15 persons participated in this activity. Students from Chalmers, together with people from Byggbrigaden and Stadsjord learned the basics of rammed earth, the experience and sensibility of Ulf with the material was crucial for the workshop.

The final result was two rammed earth planters, one with fiber and one without. The workshop was interesting and fun. The idea is to build rammed earth installations during the summer, this interventions will promote alternative building techniques and growing culture. Together with Byggbrigaden and Stadsjord we created a group called Jordstad. (http://www.jordstad.se/)

Rammed earth workshop with Ulf Henningsson (Hagy 2013)

# APPENDIX B - LEHM CONFERENCE

It was the 5th of October when Shea and I took part of the LEHM Conference. The International Conference on Building with Earth is organized by the German Association for Building with Earth (DVL), taking place every four years. People all over the world assist to this meeting where knowledge about building with earth is shared.

One of the main subjects of the conference was “New Research Findings in Earthen Buildings”, associated with the topic “Standardisation in Earth Building”. DVL was proud to inform and share the contrast between the situation 20 years ago and the present one. Earth building materials are subject to the same marketing conditions as are “conventional” mineral materials such as lime, cement or gypsum in Germany.

Another important theme in DVL´s work is the training and qualification in earthen building traditions. They have had around 170 participants since 2005 from all over Germany.

# APPENDIX C - KLARADALS KLOSTER

Last summer I got in contact with Sister Inger and the nuns in Klaradals Kloster, in Lerums municipality. Sister Inger and other nuns had the intention to build a small meditation house.

Since the first meetings sister Inger showed interest in rammed earth. She has been part of the board to build an earthship in Sjövik, but rammed earth was something new and she found it attractive to explore.

We developed drawings, sketches and the proposal was starting to become real, but for economic reasons the project was stoped.

These type of earth constructions are not well known, and the preparations are quite complex. Costs can be higher that one expects if voluntary work is not prepared.

# APPENDIX D - STRUCTURAL CALCULATION

Calculation for the rammed earth walls in the design proposal, by Andrea Mossielo, Civil Engineering student at Chalmers. The program used was MathCad.

Actions on floor beams and earth walls:
The beam dimensions are assumed and checked for bending and shear failure

$l_b := 9m$ $\quad b_b := 215mm$ $\quad h_b := 585mm$

Glulam GL32 has the following resistance

$f_{mkb} := 32MPa$ — Characteristic Bending Resistance

$\gamma_{mglu} := 1.25$ — Partial Factor For Material Properties

$k_{modb} := 0.8$ — Modification Factor (SC2-Medium Term)

$$k_{hb} := \min\left[\left(\frac{600mm}{h_b}\right)^{0.1}, 1.1\right] = 1.003$$ Size factor

$$f_{mdb} := \frac{(k_{hb} \cdot k_{modb} \cdot f_{mkb})}{\gamma_{mglu}} = 20.532 \cdot MPa$$ Design Bending Resistance

$f_{vkb} := 3.2MPa$ — Characteristic Shear Resistance

$$f_{vdb} := \frac{(k_{hb} \, k_{modb} \cdot f_{vkb})}{\gamma_{mglu}} = 2.053 \cdot MPa$$ Design Shear Resistance

The building is an office so the following loads are assumed

$q_k := 3\,\frac{kN}{m^2}$ Imposed load for an office

$q_{self} := 0.4\frac{kN}{m^2}$ Selfweight of the floor

$q_d := 1.35 \cdot q_{self} \cdot 4.5m + 1.5 \cdot q_k \cdot 4.5m = 22.68\frac{kN}{m}$ ULS load on the beams

The maximum actions on the beam is (since simply supported)

$M_{db} := \frac{q_d \cdot l_b^2}{8} = 229.635 \cdot kN \cdot m$ Design moment

$F_{db} := \frac{q_d \cdot l_b}{2} = 102.06 \cdot kN$ Design shear

The glulam beam has a resistance given by

$W_b := \frac{\left(b_b \cdot h_b^2\right)}{6} = 1.226 \times 10^7 \cdot mm^3$ Moment of the section

$\sigma_{vb} := \frac{M_{db}}{W_b} = 18.726 \cdot MPa$ Bending stress due to vertical load

$\frac{\sigma_{vb}}{f_{mdb}} = 0.912$ **Less than 1 --> OK**

Force on the earth walls

$$\sigma_w := \frac{F_w}{A} = 1.582\,\text{MPa}$$

$$\sigma_{earth} := 4\text{MPa}$$

$$\frac{\sigma_w}{\sigma_{earth}} = 0.396$$

# APPENDIX D - LAYOUT DESIGN PROCESS

To define the layout of the office I used the Neighbourhood Planning approach. To support new forms of work we need to understand the relationship between employees and their places of work.

Neighborhood Planning is a process by which a business creates a mix of open and closed, individual and group spaces based upon the needs and work patterns of particular teams. (Gillen, 2006)

The need to accommodate office workers from 9.00 to 5.00 is being replaced by the need to accommodate dispersed communities of more or less independent collaborators across virtual and physical space. (Gillen, 2006)

Neighbourhood Planning is an interesting approach to create spaces for a knowledge based company, a marketing or consultant office often employes people that do not work all week in the same building, (some of them work from home some days). It would be wise not to have an empty desk for a couple of days, empty spaces are not costly efficient.

The ideals of Neighbourhood Planning are:

1.Understand work patterns - describe what people do, work patterns should be comprehended by levels, analysing each department separated.
2.Match work patterns to settings - a setting is a space, a meeting room, a coffee place, etc.
3.Develop a menu of spaces - a short list of settings should be created to illustrate the range of spaces and the possible configuration of neighbourhoods.
4.Develop neighbourhoods of spaces - defining the layout according to work patterns.

5.From Neighbourhoods to “Workscapes” - the Neighbourhood Planning approach takes into account spaces outside the office as well as inside.
6.From Workscapes to a distributed Real State Strategy - business drivers such as multiple locations, virtual teaming, rental prices and transport links have an impact on the location, quality and quantity of an organisation´s real state.

Points 5 and 6 were not considered in the layout desing but are mentioned as suggested by Nicola M. Gillen in the book in the book *Reinventing the Workplace.*

## RE-OFFICE NEIGHBOURHOOD PLANNING

1. Understanding work patterns by level.

| LEVEL | WORK PATTERN |
|---|---|
| Core | Senior manager |
| | Project manager |
| | Virtual |
| | Team leader |
| | Research resident |
| Staff | Reception |
| | Administration |
| | Technical, support |
| External | Cleaning |
| | Food, coffee |
| | Commerce |

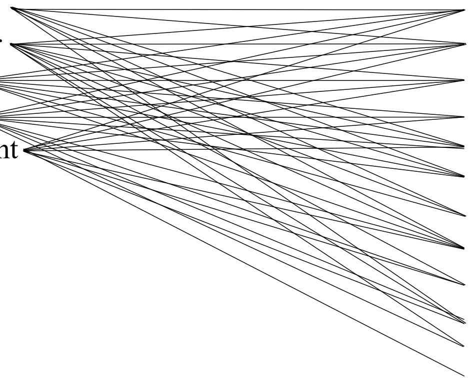
2.Match work patterns to setings by level

| LEVEL | SETTINGS |
|---|---|
| Core | Conference room |
| | Fika room |
| | Copy room |
| | Individual work module |
| | Hot Desking (project group work)* |
| | Booking room |
| | Private room |
| | WC/HWC |
| | Storage |
| | Resting room |
| | Site |
| | Printing room |
| | Kitchen |
| Staff | Lobby |
| | Kitchen |
| | Janitors office (Vaktmästeri) |
| | Mechanical room |
| | WC/HWC |
| External | Stores |
| | Terrace |
| | WC/HWC |

*Hot Desking is a concept in office design were employees shuffle between open tables, couches and working stations, it enhances greater collaboration and innovation among co-workers.

CORE

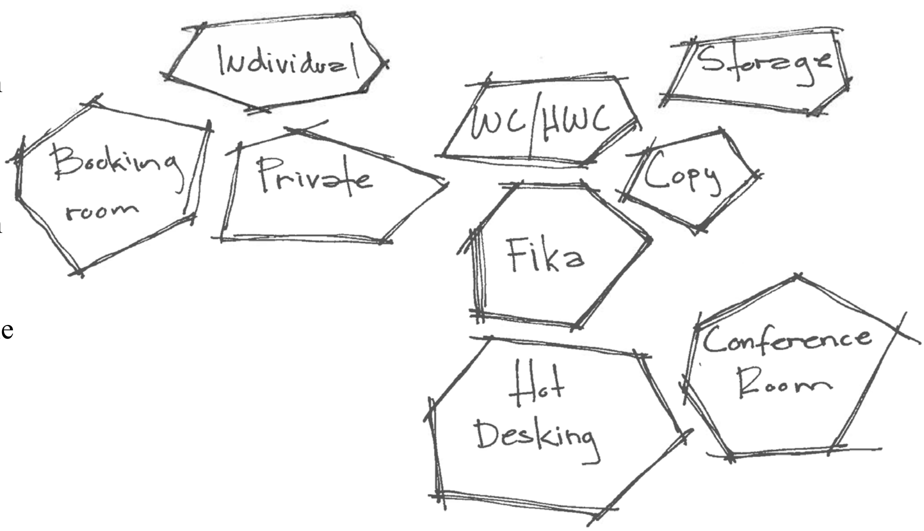
Senior manager
Project manager
Virtual
Team leader
Research resident

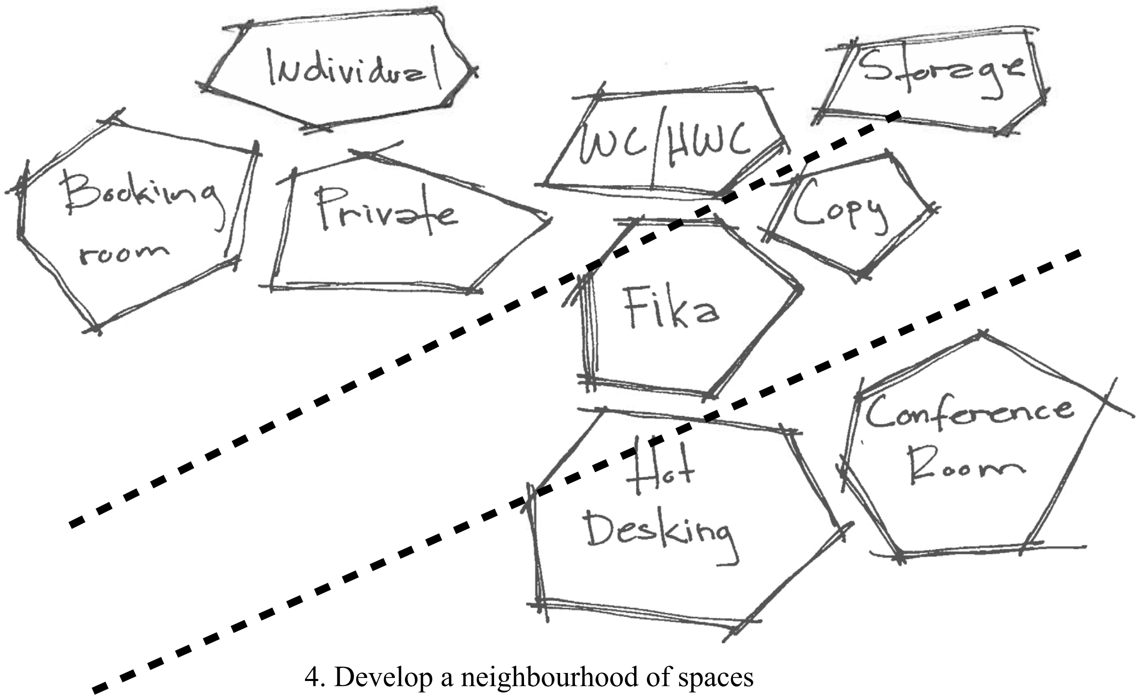


Conference room
Fika room
Copy room
Individual module
Hot Desking
Booking room
Private room
WC/HWC
Storage
Resting room
Site
Printing room
Kitchen

3. Develop a menu of spaces

1.Fika room
2.Conference room
3.WC/HWC
4.Hot Desking
5.Copy room
6.Conference room
7.Private room
8.Booking room
9.Individual module
10.Resting room
11.Storage

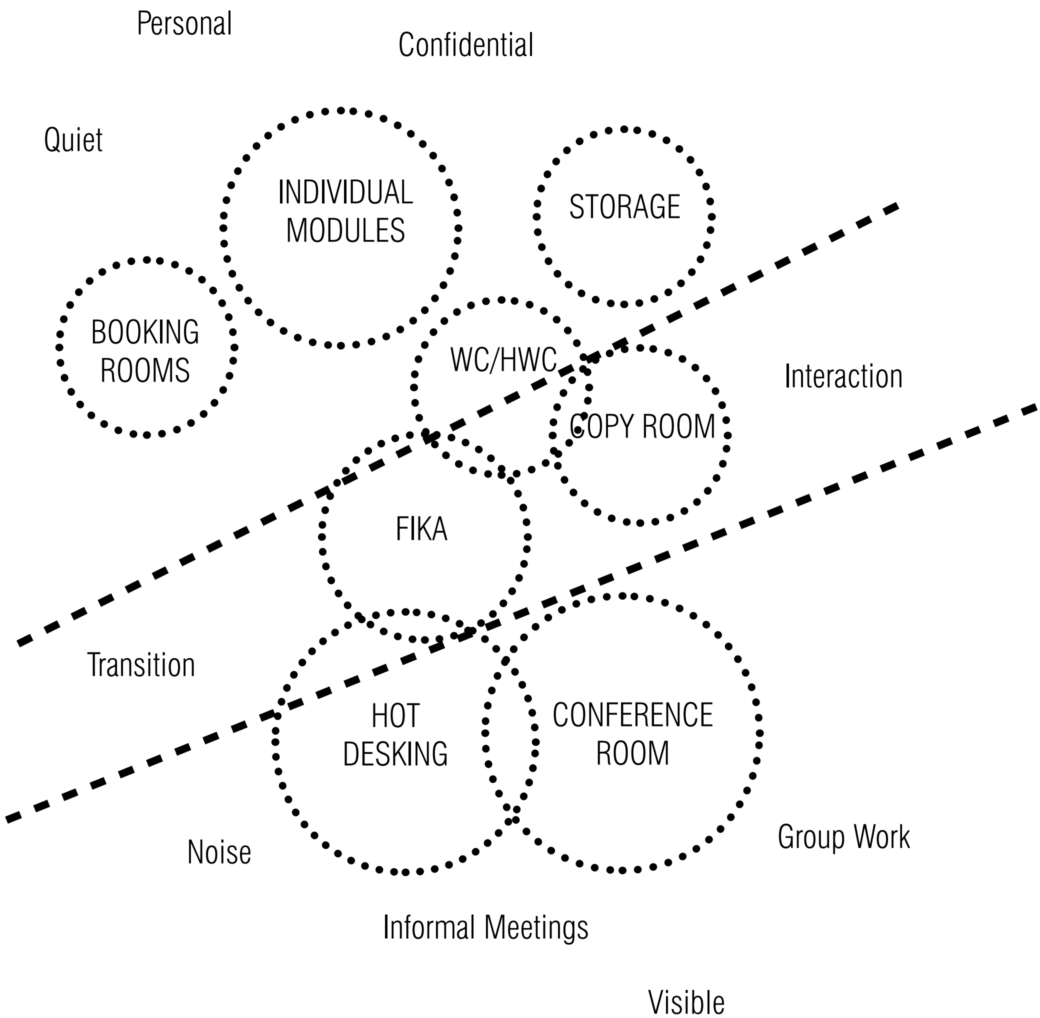





4. Develop a neighbourhood of spaces

There are two main groups of spaces, the first one consists in open and visible areas like conference room and hot desking. The work is focused in project groups, where temporary tasks and informal meetings take place. The characteristics of these spaces is that they enchence gathering and communication.

The second group of spaces is private areas, individual tasks and confidential work is carried out in these areas. There is a gap, a “street” that is a transition space between the noise and the quiet, a fika room is placed in between the two groups.


Personal
Confidential
Quiet
INDIVIDUAL MODULES
STORAGE
BOOKING ROOMS
WC/HWC
COPY ROOM
Interaction
FIKA
Transition
HOT DESKING
CONFERENCE ROOM
Noise
Group Work
Informal Meetings
Visible

# REFERENCES

# BIBLIOGRAPHY

Bennett, D. (2010) *Sustainable Concrete Architecture*. London: RIBA Publishing

Boltshauser, R., Rauch, M. (2009) *Haus Rauch. A Model of Advanced Clay Architecture*. Berlin: Birkhäuser

De Saulles, T. (2012) *Thermal Mass Explained*. UK (Report TCC/05/11)

Easton, D. (2007) *The Rammed Earth House*. US: Chelsea Green Publishing

Ekblom, A. (1986) *Om Hus av Jord och Lerhalm*. Göteborg: Chalmers tekniska högskola (Examensarbete vid Arkitektur)

Fissabre A., Wilson, A., (2012) *Contrasting Ideologies of Sustainability in Earth Building Literature.* 5-6 October, 2012. Weimar, Germany

Guillard, H., Houben, H. (1994) *Earth Construction. A Comprehensive Guide.* London: Intermediate Technology Publications

Kapfinger, O., Singer, A. (2010) *The Rauch House.* Basel: Birkhäuser Verlag

Kermani, A. (1999) *Structural Timber Design.* UK: Blackwell Science LTD

Lindberg, C., Molin, K., (1950) *Jordhusbygge. Arbetsbeskrivningar och Ritningar.* Stockholm

Lindberg, E. (2002) *Gjort av Jord. Lerjord som byggmaterial i Sverige och länder med likartat klimat*. Stockholm: Kungl tekniska högskolan (Examensarbete vid Arkitektur)

Minke, G. (2000) *Earth Construction Handbook. The Building Material Earth in Modern Architecture.* UK: WIT Press

Minke, G. (2009) *Building with Earth. Design and Technology of a Sustainable Architecture*. Berlin: Birkhäuser

Morgan, W. (2008) *Earth Architecture. From Ancient to Modern*. University Press of Florida

Parton, H., Zumstein, K. (2011) *Total Office Design. 50 Contemporary Workspaces.* London: Thames and Hudson Ltd

Rael, R. (2009) *Earth Architecture.* New York: Princeton Architectural Press

Röhlen, U., Ziegert, C. (2011) *Earth Building Practice. Planning, design, Building.* Berlin: Bauwerk Beuth

Samp. (2007) *Straw and clay*. Stockholm: EO Grafiska

Van Lengen, Johan (2011) *Manual del Arquitecto Descalzo.* México D.F.: Árbol Eeditorial

Vindrosen, T. (1993) *Lerjord som byggmateriale. Vejledning.* Kobenhavn K: BUR/Byggeriets Udviklingsrad

Worthington, J. (2006) *Reinventing the Workspace.* Oxford: Architectural Press

# IMAGE REFERENCES


6. Ahora Diario (2012) *Sustitución de Casas de Cartón* [Online Image] Ahora Diario. http://www.ahoradiario.mx/2012/07/sustitucion-de-casas-de-carton-cambia-la-vida-de-familias-pobres/ (04 May 2013)

14. Earth Construction (Unknown illustrator) (1994) *Universality of earth buildings* [Illustration] *In* Earth Construction. A Comprehensive Guide. Guillard, H., Houben, H. p.6. London: Intermediate Technology Publications

15. Cutler Anderson Architects (2010) *Bodega Residence* [Online Image] Cutler Anderson Architects. http://cutler-anderson.com/project/bodega-bay (13 Sep. 2012)

16. Iñigo García Odiaga (2012) *Construir allí* [Online Image] Vaumm Architecture and Urban Planning. http://vaumm.blogspot.se/2012/07/construir-alli.html (05 Feb. 2013)

20, 84. Jones Studio (ca 2012) *Lacey Residence* [Online Image] Jones Studio. http://jonesstudioinc.com/public/36/index.htm (17 Oct. 2012)

21. Architects Rudanku & Kankkunen (ca 2011) *Sao Paolo Vocational School* [Online Image] Architects Rudanku & Kankkunen. http://www.rudanko-kankkunen.com/our_work/ (17 Oct. 2012)

21. Toshihiro Sobajima (2011) *Earth Bricks* [Online Image] Atelier Tekuto. http://www.tekuto.com/blog_eng/wp_english/wordpress/?p=760 (17 Oct. 2012)

22. AbeySmallcombe (ca 2001) *Cob Visitor Facility, Melon Car Park* [Online Image] AbeySmallcombe. http://abeysmallcombe.com/projects-completed.htm (17 Oct. 2012)

27. Trek Exchange LLC (ca 2001) *La Ahlambra* [Online Image] Trek Exchange LLC. www.trekexchange.com/tours/110 (20 Oct. 2012)

29. Jordhusbygge (1950) *Ett förnämligt svenskt jordhus* [Image] *In* Jordhusbygge. Arbetsbeskrivningar och Ritningar. p.7. Stockholm

33. Rammed Earth Builders (2012) *Rammed Earth Form Work* [Online Image] Rammed Earth Builders. http://rammedearthbuilders.com/rammed-earth-form-work/ (15 Feb. 2013)

37. Mariana Correia & Jacob Merten (2011) *Steninge* [Online Image] Terra Incognita. http://culture-terra-incognita.org/index.php?option=com_content&view=article&id=64&Itemid=66&lang=fr (28 Oct. 2012)

38. Jordhusbygge (1950) *Ett förnämligt svenskt jordhus* [Image] *In* Jordhusbygge. Arbetsbeskrivningar och Ritningar. p.7. Stockholm

42. Loles Casado (2010) *Torres en la Alhambra* [Online Image] Flicr. http://www.flickr.com/photos/migube/5825605010/ (28 Oct. 2012)

43. Santiago Quesada Arquitectos asoc (2004) *Galería de Torre de Gontar* [Online Image] Picasa. http://picasaweb.google.com/lh/photo/2Q2qDVDrfJPJ7Q71AlhV-Q (24 Oct. 2012)

43. Àngels Castellarnau (2012) *Textura Calicostrado* [Online Image] Periferia Arquitectura y Sostenibilidad SCP. http://periferiablog.blogspot.se/2012_05_01_archive.html (24 Oct. 2012)

46. Ryan Pyle (2009) *A woman carries baskets full of goods across a river near a cluster of traditional Hakka Tulou homes in the county of Yongding, China* [Online Image] Global Post. http://www.globalpost.com/dispatch/worldview/090930/full-frame-chinese-rural-dwellings (24 Oct. 2012)

# IMAGE REFERENCES

47. Xinhua (2012) *Tourists visit Tulous in Yongding, Fujian* [Online Image] China.org.cn. http://www.china.org.cn/travel/2012-09/06/content_26446322_5.htm (23 Oct. 2012)

48. Jens Aaberg-Jørgensen (ca 2000) *Zhenchenglou* [Online Image] Clan Homes in Fujian. http://www.chinadwelling.dk/ (23 Oct. 2012)

50, 79, 164, 165, 166. Beat Bühler, Martin Rauch (ca 2008) *House Rauch* [Online Image] Lehm Ton Erde. http://www.lehmtonerde.at/en/projects/project.php?pID=7 (24 Oct. 2012)

55. Petro Tech Associates (2004) *Kaolinite 2, Smectite-Illite 2* [Online Image] Petro Tech Associates. http://www.petrotech-assoc.com/prod01.htm (22 Jan. 2013)

65. David Mudd (2010) *Natchez Trace Parkway Bridge in Williamson County, TN* [Online Image] Livability. http://livability.com/franklin/tn/attractions/natchez-trace-parkway-celebrating-75th-anniversary (14 Feb. 2013)

75. Dialog (2013) *A Million Pounds of Mud* [Online Image] Dialog. http://www.designdialog.ca/projects/nkmip-desert-cultural-centre/ (07 Feb. 2013)

76, 77, 95, 96. Sirewall (2013) *Portfolio* [Online Image] Sirewall Inc. http://www.sirewall.com/portfolio/commercial-projects/just-grapes/ (10 Feb. 2013)

78. Tom Stoelker / AN (2012) *Textured detail of rammed earth* [Online Image] The Architects Newspaper. http://archpaper.com/news/articles.asp?id=5986 (10 Feb. 2013)

78. Iwan Baan (2012) *Heringer created the strié mud layers with the help of artist Martin Rauch* [Online Image] The Architects Newspaper. http://archpaper.com/news/articles.asp?id=5986 (10 Feb. 2013)

79. Beat Bühler (ca 2008) *Rammed earth house, Rauch family home* [Online Image] Architonic. http://www.architonic.com/aisht/rammed-earth-house-rauch-family-home-boltshauser-architekten/5100620 (24 Oct. 2012)

80, 90, 91. Ralph Feiner, Martin Rauch (2010) *Stable Plazza Pintgia* [Online Image] Lehm Ton Erde. http://www.lehmtonerde.at/en/projects/project.php?pID=34 (31 Jan. 2013)

81. Torsten Seidel (2011) *Lehmhaus in Ihlow* [Online Image] Baunetz Wissen Solar. http://www.baunetzwissen.de/objektartikel/Solar_Lehmhaus-in-Ihlow_72748.html (01 Nov. 2012)

82. Kendle Design Collaborative (2011) *Desert Wing* [Online Image] Kendle Design Collaborative. http://kendledesign.com/portfolio/residential/desert-wing.html (12 Feb. 2013)

83. Nez Architects / Loco Architects (2005) *Zousei* [Online Image] Nez Architects / Loco Architects. http://takenez.com/works/works_zousei.html (12 Feb. 2013)

84. Luis Gordo (2011) *Rammed Earth and Stone Buildings Make Up Oaxaca School of Plastic Arts* [Online Image] Inhabitat. http://inhabitat.com/rammed-earth-and-stone-buildings-make-up-oaxaca-school-of-plastic-arts/luis-gordoa-oaxaca-plastic-arts-taller-de-arquitectura-mauricio-rocha-8/?extend=1 (12 Feb. 2013)

92. Building with Earth (Unknown illustrator) (2009) *The world´s most earthquake-prone regions* [Illustration] *In* Building with Earth. Design and Technology of a Sustainable Architecture. Minke, G. p136. Berlin: Birkhäuser

94. Bonny Makarewicz (2010) *Finished and ready to move Rammed Earth House* [Online Image] RDC Fine Homes. http://www.rdcfinehomes.com/category/rammed_earth_house/ (13 Oct. 2012)

167, 168, 169. Cutler Anderson Architects (2010) *Meteor Vineyard* [Online Image] Cutler Anderson Architects. http://cutler-anderson.com/project/bodega-bay (13 Sep. 2012)

# DIGITAL REFERENCES

Diario, A. (2012) Sustitución de casas de cartón, cambia la vida de familias pobres. Ahora Diario, 20 july. http://www.ahoradiario.mx/2012/07/sustitucion-de-casas-de-carton-cambia-la-vida-de-familias-pobres/ (2013-05-04)

Fix, S. (2009) Viability of Rammed Earth Building Construction in Cold Climates. Ryerson University

Liljemalm, A. (2012) Lera i överflöd vid nästa tunnelbygge. Göteborgs-Posten, 04 mars. http://www.gp.se/nyheter/goteborg/1.1340120-lera-i-overflod-vid-nasta-tunnelbygge (2013-05-20)