Building with earth in a cold climate

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Abstract

The climate crisis is one the biggest challenges that have ever faced humanity. The building industry is responsible for almost 40% of all emissions. Looking at the high emissions from many commonly used building materials, changes in choice of material have the potential for making great impacts on the total emissions of the building industry.

The low emission material, earth, is not a new building material. It has been used for thousands of years, and even today, one third of the planet's population lives in houses made from earth, mostly in warm climate developing countries. Earth, being a widely available material across the globe, has the potential to become a common building material in colder climates.

In this master thesis, first, the advantages of earth are explored, including sustainability, recyclability, and relative humidity regulation. The challenges of building in a cold climate are then found, in addition to their impact on earth building. Lastly, how to solve these challenges are studied, including erosion, moisture control, thermal mass, and insulation. In each of these categories, factors that could impact the performance and advantages are identified, in the form of criteria.

Existing earth buildings in Europe are used as reference projects, to compare them, and the climate they are located in, in order to discover trends and similarities. Three projects, which are close in scale and function of the redesign of a rowhouse which will take place in the end of this thesis, are then studied closer as case studies. The different solutions in the case studies are evaluated using the criteria, created in the theoretical part, and effectiveness and relevance is discussed.

The results from the reference projects and case studies are then used as a base for the redesign of a rowhouse in Höganäs, Sweden. Four suggestions for a redesign have been made. The differences are representing priorities when building with earth in a cold climate. The purpose of this is to see how this rowhouse could have been built, had it been built in earth.

Keywords: Earth, sustainability, indoor climate, cold climate

"Soon, material, not time, will be our most precious commodity"

- Annette Spiro, 2019, Upscaling Earth, p. 7

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Student background

Education

2017-2020	Aalborg University Aalborg, Denmark Bachelor of Science (BSc) in Engineering (Architecture and Design)
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As architects, we have the power to make sustainable choices for many more beyond ourselves. We can choose to work with sustainable materials, sustainable solutions, and recycling. In this thesis, my goal was to explore and understand one sustainable material, that I hopefully will have the opportunity to work with, in my coming career as an architect.

Sustainability is something that I became engaged in during my studies in architecture, and that will continue to shape my work as a designer. The potential for improvement cannot be exaggerated enough. I dream of a world where the building industry is known as a sustainable one.

Table of content


Introduction

Introduction

Background

Global warming is one of the great challenges that the world is facing today. In 2018 the UN Intergovernmental Panel on Climate Change (IPCC) released a report on the state of global warming today, and the consequences that will take place if emissions are not cut drastically (Watts, 2018). The authors of the report say that significant changes are needed to keep the global temperature from rising more than 1,5°C compared to pre-industrial levels. If nothing is done, the risks of floods, drought, extreme heat, and poverty for hundreds of millions of people will significantly increase (Watts, 2018).

The building and construction industry was responsible for 36% of final energy use, and 39% of carbon dioxide emissions in 2018, according to the International Energy Agency's report 2019 Global Status Repost for Buildings and Construction (2019). 11% of this was accounted for as a result of the manufacturing of materials like glass, cement, and steel (International Energy Agency, 2019). Spreading information about low-carbon materials and technologies, like for example earth, to professionals in the construction and building design industry, is mentioned as an action to increase the sustainability when talking about building materials (International Energy Agency, 2019).

Earth has a low embedded energy compared to many other conventional building materials. The embedded energy is the information of how much energy the mining, manufacturing, and transportation is required to produce a material. Earth has an embodied energy of 5-10 kWh/m3. Compared to materials like concrete (600-800 kWh/m3) and solid fires brick (1140 kWh/m3), earth has many times over a more environmentally friendly profile (Egenti & Khatib, 2016). Earth is a material that can be used again and again. Earth can be recycled an immeasurable amount of times by simply folding it back into the ground to use for another earth structure or decompose. Using earth more actively can help decrease the emissions originating from the building industry.

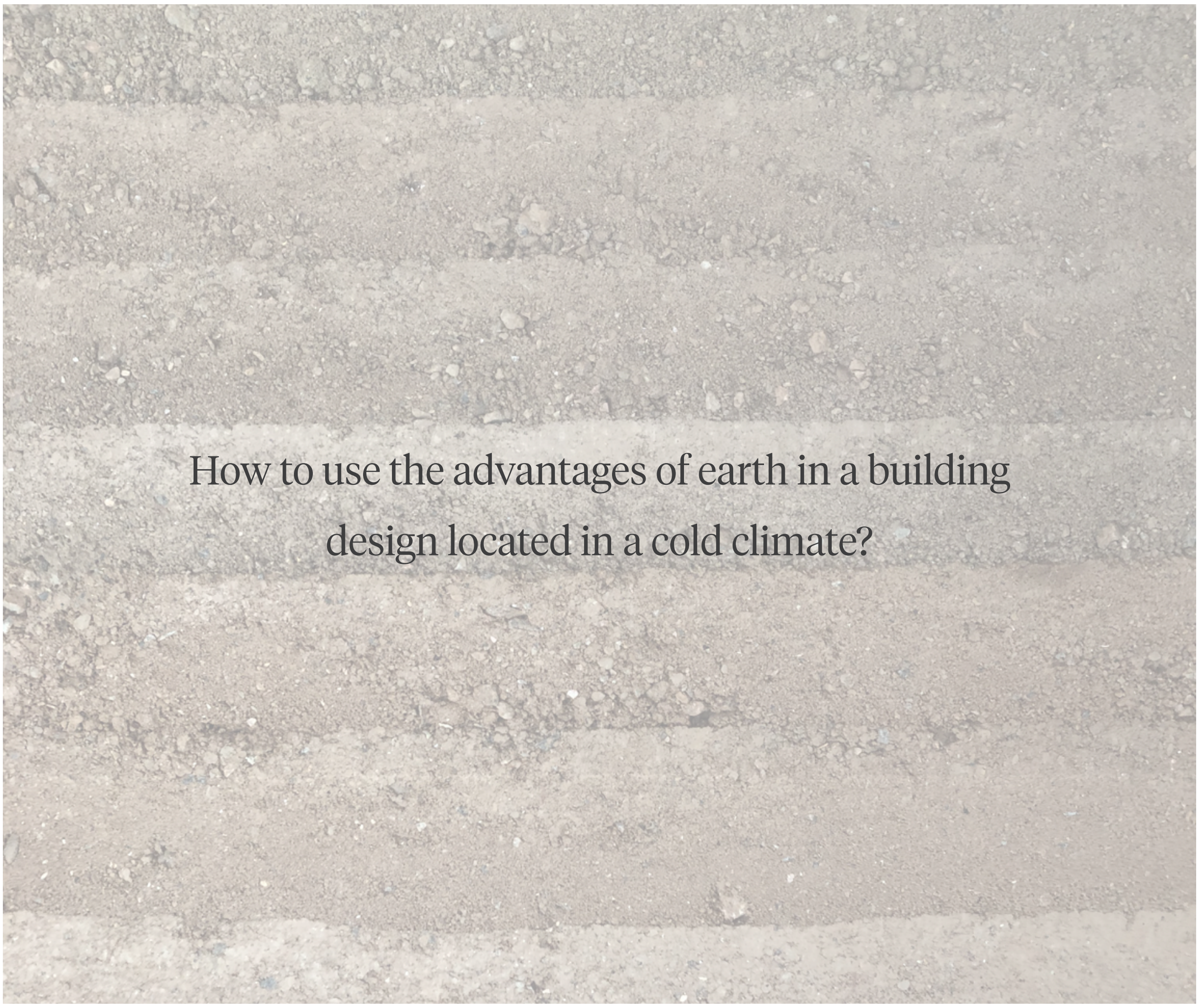
Building with earth is not a new invention. The oldest earth structure known to be built by man, dates back to 10 000 BC and is found in Mesopotamia and was made of stacked earth bricks (Vyncke et al., 2018). Earth buildings can be found all over the world, everything from vernacular houses to historical monuments. Even today, 30% of the world's population lives in earth buildings. In developing countries, as much as 50% of the population lives in buildings made out of earth. Earth can be found almost all over the world. It is therefore a material that is available locally and in addition to this, the material is cheap (Vyncke et al., 2018). On the map on the right, the spread of earth building worldwide is illustrated. Here one can see that earth buildings are mostly concentrated in the southernmost hemisphere, which reflect the warmer climate.

In Europe today, there are several examples of earth buildings. From the 13th to the 17th century earth was used as an infill material in timber-framed buildings throughout Central Europe (Minke, 2012). Earth houses built around 100-200 years ago are still inhabited. There are several examples of earth buildings in Europe that are built in recent years. It is said that earth has had a renaissance as a building material, although the movement is small. Architectural measures are taken piece by piece to overcome the challenges of durability and proving its place as a relevant building material even today.

Illustration 1. Map showing the spread of earth building around the world. (Adapted from (Vyncke et al., 2018).

Introduction

Research question



How to use the advantages of earth in a building design located in a cold climate?

Introduction

Methods and delimitations

Introduction
First, an introduction to earth as a building material is presented. Here a background and the availability of the material is de described. The framework and delimitations for the thesis are set.

Theory
Here the motivations for using earth are explained and literature studies are done to describe the advantages of earth. A definition of cold climate follows along with the challenges of a cold climate that can affect building with earth. Lastly, literature studies are done on the topics identified as challenges and other properties of earth in a cold climate.

Practice
To see how earth is built with in practice and how the design is affected by the climate they are built in, reference project and their climate are studied. Furthermore, three of the reference projects are evaluated closer as case studies. The results are discussed and used to make strategies for the redesign with earth.

Redesign
The product of this thesis will be the redesign of an existing rowhouse in Höganäs in Sweden. The strategies from the previous chapters are used as the base for four redesigns of the rowhouse illustrating how this building could have been built, had it been built in earth. The suggestions are evaluated, and advantages and challenges are discussed.

Will do:
- Explore the properties of earth
- Understand how a cold climate affects earth design
- Study existing earth buildings and use them as inspiration and guidance
- Redesign an existing rowhouse in Höganäs, Sweden

Will not do:
- Go into detail on the economics of earth
- Go into detail on the structural properties of earth
- Go into detail on the history of using earth as building material


Earth and its potential

Earth and its potential

Introduction

In the chapter “Earth and its potential”, theory on the advantages and challenges of building with earth are presented. All the different properties of earth are referred to as categories. The purpose of this chapter is to create criteria in each of the categories which will be used as guidelines to evaluate existing earth buildings, to see to what degree they have made use of the advantages and solved the challenges of building with earth. These will be used to evaluation earth buildings later on.

The advantages of earth are presented first. They can be a motivation and the reason ‘why’ to build with earth, and these are: Embedded energy, recyclability, and relative humidity regulation. These properties will be “the benefits” of the rowhouse redesign at the end of the booklet. The criteria here factors that have an impact of the degree of effect of the advantage.

Secondly, the definition of a cold climate is presented, as well as the challenges that comes with it. This will give an understanding of the climate of Höganäs, identify challenges, and how the challenges can affect and are managed in earth design.

Challenges and properties of earth in a cold climate are presented lastly. They are divided into two groups: Material and Comfort, which concerns respectively the properties of earth in a cold climate, and the comfort of living in an earth building in a cold climate. The criteria here are factors or solutions that will help solve the challenges.

From this point and on in this booklet all the aforementioned properties and aspects of building with earth will be referred to as categories. At the end of each category a conclusion and criteria can be found in green text. The criteria are all listed at the end of the chapter.

Why build with earth?

Embedded energy

Since the middle of the 20th century, there has been a search for sustainable development in the building industry. The need to build environmentally responsible houses has increased. Institutions, schools, research centres, organisations, and individuals have been researching, developing, and promoting earth as a sustainable building material (Egenti & Khatib, 2016).

Earth, in comparison with many other building materials, has a low embedded energy. Embedded energy is the energy used for mining, manufacturing, and transporting to produce a material. Earth has an embodied energy of 5-10 kWh/m3. Compared to materials like concrete (600-800 kWh/m3) and solid fires brick (1140 kWh/m3), earth has many times over a more environmentally friendly profile (Egenti & Khatib, 2016). Careless use of energy-intensive materials is both wasteful and pollutes the environment (Minke, 2012). Even wood, which is known to be a material with a low embedded energy, has a higher embedded energy compared to earth. According to Heringer et al. (2019), the embedded energy of wood is around 2,7 times higher than earth.

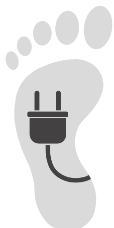
Cement is often added to earth for several reasons. The embodied energy in cement is 2640 kWh/m3, (Egenti & Khatib, 2016) and by adding this to earth, the total embodied energy in the material will increase significantly, even with small amounts of cement. In rammed earth buildings stabilised with cement there is usually around 5%-10% cement (Heringer et al., 2019). In a compressed earth block (CEB) with 5% cement, the cement stands for 30% of the grey energy (Grünacker, 2021).

Almost everywhere, in almost every region of the world, earth is available as a building material (Vyncke et al., 2018). Many times the material can even be excavated for the site the actual building is going to be built on, or nearby. By using local materials, the need for transportation of the material is drastically lowered. In the cases where the earth is excavated from the building site, the emissions from transportation will be non-existent. Since earth is broadly available almost everywhere, the need for transportation will be significantly lower than other building materials that have to be produced in a factory far away.

Earth has a significantly lower embedded energy than many other building materials. Using earth as a building material will lower the need for other building materials, and therefore lower the pollution of the environment. Adding cement to earth will increase the material's embedded energy. Earth can be found almost everywhere in the world, and using the material can significantly lower the need for material transportation. Using a local material, like earth, lowers the need for other more energy-consuming materials with a greater need for transportation.

In the redesign of the rowhouse in Höganäs, earth should be the main building material, possibly in combination with other materials with low embedded energy, to keep the total embedded energy as low as possible. The earth will not contain cement, which will stabilise it, however also increase the embedded energy. Earth should be imagined excavated locally.

Criteria:
- +1 no cement in earth
- +1 building mainly consist of earth or other low embedded energy materials
- +1 use of locally excavated earth



Material	Energy consumption (kWh/m^3)
Cement (PC)	2640
Fired brick (solid)	1140
Chipboard	1100
Lime	900
Plasterboard	900
Concrete block	600-800
Fired brick (perforated)	590
Calcium silicate brick	350
Natural sand / aggregate	45
Earth	5-10
Straw (baled)	4,5

Table showing the embedded energy of building materials. (Data from Egenti & Khatib, 2016)

Why build with earth?

Recyclability

Earth is a material that can be used again and again. The material can be recycled an immeasurable number of times over a long period of time. In this way, earth will never become a waste material that pollutes the environment (Minke, 2012).

Unbaked earth can be reused. The material is then simply folded back into the ground, should be the use of the structure no longer be of use. The earth can then be reused for other buildings or structures or decompose in the ground (Minke, 2012).

Adding cement, or other chemically based additives will recuse the recyclability of the earth significantly. The stabilisation makes it so the earth cannot be torn down as easily as with untreated earth (Heringer et al., 2019). Surface treatments, that consist of non-earthen materials, and are difficult to remove from an earth surface, will also complicate the process of recycling the earth.

Earth, if untreated, is a material that can be reused an unmeasurable number of times. Adding cement, or other chemical-based additives will make tearing down an earthen structure after its lifetime significantly more difficult and impossible to fully recycle. Non-earthen surface treatments can also reduce the recyclability if the treatment is difficult to remove.

In the redesign of the rowhouse in Höganäs, the earth should not be stabilised, as it will make the earth harder to recycle. The earth should not be treated with a non-earth surface treatment that will be hard to remove.

Criteria:
- +1 raw earth with no stabilisers
- +1 no surface treatment that is hard to remove

Relative humidity regulation

Relative humidity

When entering a room, the temperature is one of the first impressions people get, because it is easy to determine if it is too hot or too cold. The level of humidity, on the other hand, can be harder to determine even though the air humidity makes an impact on the experienced comfort in a room. During longer periods of time, the air humidity will have a significant impact on the health of people (Minke, 2012).

A relative humidity lower than 40% can make people more receptible to colds and related diseases. This is because dust, bacteria and viruses are usually absorbed by the mucous membrane and then returned out through the mouth, but when exposed to a too low relative humidity, it dries out and disturbs the transportation system (Minke, 2012). This will make the lungs more susceptible to health problems.

Positive consequences like reduction of fine dust in the air, reduction of many bacteria and viruses, reduction of odour and static charge on surfaces, and activation of protection mechanisms in the skin against microbes can be achieved and a relatively high humidity content of up to 70% (Minke, 2012).

At a relative humidity of above 70% or 80% fungus formations grow rapidly in closed rooms. Breathing in fungus spores over time can lead to allergies and various pains (Minke, 2012). In addition to this, too high of a humidity content can feel unpleasant to be in, in warm weather, probably caused by the lowered oxygen intake in the blood. Therefore, the relative humidity level in a room should be higher than 40% while still lower than 70% (Minke, 2012).

Temperature and relative humidity

In cold climates, the temperature difference between inside and outside can be significant, especially during the cold season. Then, if too much of the outside air enters a room, it will make the air in the room dry. This is because even if the relative humidity content is high outside in the cold air, the relative humidity level will be lowered significantly as the air warms up inside. For example, if the outside air has a relative humidity of 80%, a temperature of 0°C, and is warmed up to 20°C, the relative humidity drops to around 25% (Minke, 2012).

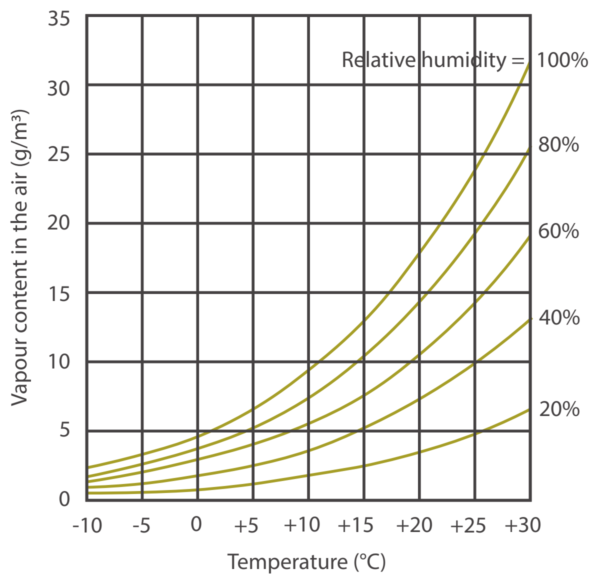


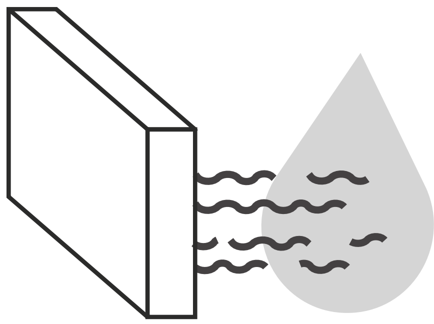
Illustration 2. Relationship between temperature and relative humidity. (Data from Minke, 2012).

Why build with earth?

Relative humidity regulation

Earth and humidity

Humidity can be absorbed and desorbed to the air from porous, and the effectiveness of this is dependent on the speed of absorption and desorption of the material. Experiments performed at the Building Research Laboratory of the University of Kassel in Germany show that the outermost 1,5 cm thick layer of a 1 m^2 mud brick wall can absorb around 300 g of water in 48 hours, if the humidity level of the surrounding air goes from 50% to 80%. In the same experiment done with sandstone and pinewood, the results were about 100g/m^2, plaster 26 to 76 g/m^2, and baked bricks 6 to 30 g/m^2 (Minke, 2012).



In an experiment with both sides of an 11,5 cm thick wall of different materials, the humidity level was raised from 30% to 70%. After 16 days it shows that silty loam, clayey loam and straw loam absorbed the most water, respectively about 870 g/m^2, 790 g/m^2 and 630 g/m^2. Solid brick, cement concrete and cement concrete absorbed the least water, respectively about 70 g/m^2, 50 g/m^2 and 20 g/m^2 (Minke, 2012).

In a room with a floor area of 4 x 3 meters, a height of 3 meters, and a wall area of 30 m^2 mud bricks, the walls would absorb 9 litres of water in 48 hours if the air humidity level was raised from 50% to 80%, according to an experiment done at Building Research Laboratory. If the humidity level was lowered down to 50% again, the mud brick walls would release the same amount of water it absorbed. In the same experiment, but with baked brick walls, the amount of water absorbed would be 0,9 litres of water (Minke, 2012).

In a house in Germany with exterior and interior walls made of earth, measurements were made over a period of five years. The relative humidity level in this house remained almost constant during the years, fluctuating between 45% and 55% (Minke, 2012). This shows that earth is a suitable material to balance the humidity levels indoors at a comfortable level, both absorbing and desorbing water, adapting to the conditions.

Weather protection of earth surfaces

There are multiple ways to treat an earth surface to make it more weather resistant. Plasters and paints can harden the surface or make it more water-repellent. Other examples of this can be linseed oil and lime washes (Minke, 2012).

The water repellent agent penetrates the pores of the earth. However, these surface treatments can significantly lower the capillary action and vapour diffusion and therefore lowers earth's ability to regulate the humidity level inside a room. Therefore, applying paints or other water repellents to protect earth surfaces from weathering should not be done unless necessary, as it will decrease the vapour diffusion of the earth wall.

In colder climates, this is especially important. If water condensates inside a wall and is hindered to go through the surface, the water can be trapped which could lead to rot inside the wall (Minke, 2012).

Adding cement to earth, will make the earth not water-soluble anymore (Rauch, 2015). If the earth is not water-soluble, the earth is no longer capable of absorbing and desorbing humidity in the air as well as untreated earth. Therefore, adding cement will hinder the earth from balancing the indoor moisture content at a comfortable level.

The air humidity in a room can make a significant impact on the health of people. Relative humidity of between 40% and 70% is beneficial because it will protect the body while avoiding bacteria and fungus. Earth can preserve materials like wood, because of the lower water content in earth than wood, which prevents insects and fungus from growing. If the percentage of organic material is too high, the earth can rot. Raw untreated earth will keep the relative humidity at around 45%-55%. Adding cement or surface treating earth can lower the property of balancing the relative humidity at a comfortable level.

In the redesign of the rowhouse in Höganäs, the earth should neither be stabilised nor surface treated, in a way that hinders the relative humidity regulation. Earth should be the primary surface material inside, allowing there to be enough surface to regulate the relative humidity.

Criteria:
- +1 raw earth with no stabilisers
- +1 no non-earthen or water-repellent surface treatments
- +1 if earth is the primary inside surface material

Cold climate and its challenges

Cold climate

Dfb

In Höganäs in Sweden, there is a humid continental climate according to the Köppen climate classification system. The climate is a cold climate with no dry season and warm summers, which can be described with the letters “Dfb” according to the climate classification (Beck et al., 2018). It is this climate that is referred to as a cold climate in this master thesis. This climate is found in the southern half of Sweden, larger parts of eastern Europe, and smaller parts of Canada and Japan (Beck et al., 2018).

Dfb – cold, no dry season, warm summer

- Coldest month with a temperature below 0 °C
- All months with temperature average below 22 °C
- At least four months with temperature average above 10 °C
- No significant difference in precipitation between seasons

(Beck et al., 2018)

Illustration 3. Map showing spread of Dfb - cold climate locations worldwide. (Data from (Beck et al., 2018).

Challenges

Temperature

The temperature in a cold climate makes extra insulation necessary in a building, compared to buildings built in warm climates. But temperatures below the freezing point can be a problem for the material itself. Water expands as it freezes, which can cause problems if water is trapped inside the material, like water in earth.

Temperatures below the freezing point can affect the choice of earth composition if using earth as a façade material. In a test performed described in Building with Earth by Gernot Minke (2012), two earth samples with a different ratio of clay are exposed to weathering for three years. The first sample contained 40% clay, while in the second, sand was mixed in, thinning the clay content down to 16%. When the two samples had dried, the first clayey sample had shrunk 11%, and the second less clayey sample had shrunk 3% (Minke, 2012). In the clayey earth sample, thin hairline cracks were created during the drying period. After the three years, water had entered the hairline cracks through capillary action. When temperatures had dropped below the freezing point, the water expanded, causing damage to the outmost layer of the sample, looking as if it had started scaling (Minke, 2012). In areas with no visible hairline cracks, this frost erosion did not occur. In the second less clayey earth sample, the outermost layer of earth had been washed away due to rain. However, no hairline cracks were observed and after the three years, no frost erosion either. This is due to the fact that the pores in the earth mixture were larger and thus allowing the water to expand (Minke, 2012). In areas with temperatures below the freezing point, earth with a high clay content should not be used as the outermost layer on exterior walls, as the risk of frost erosion is high in clayey earth exposed to freezing temperatures.

In Höganäs, where the temperature sometimes drops below 0 °C, the façade material of earth buildings, if made of earth, should not have a too high percentage of clay.

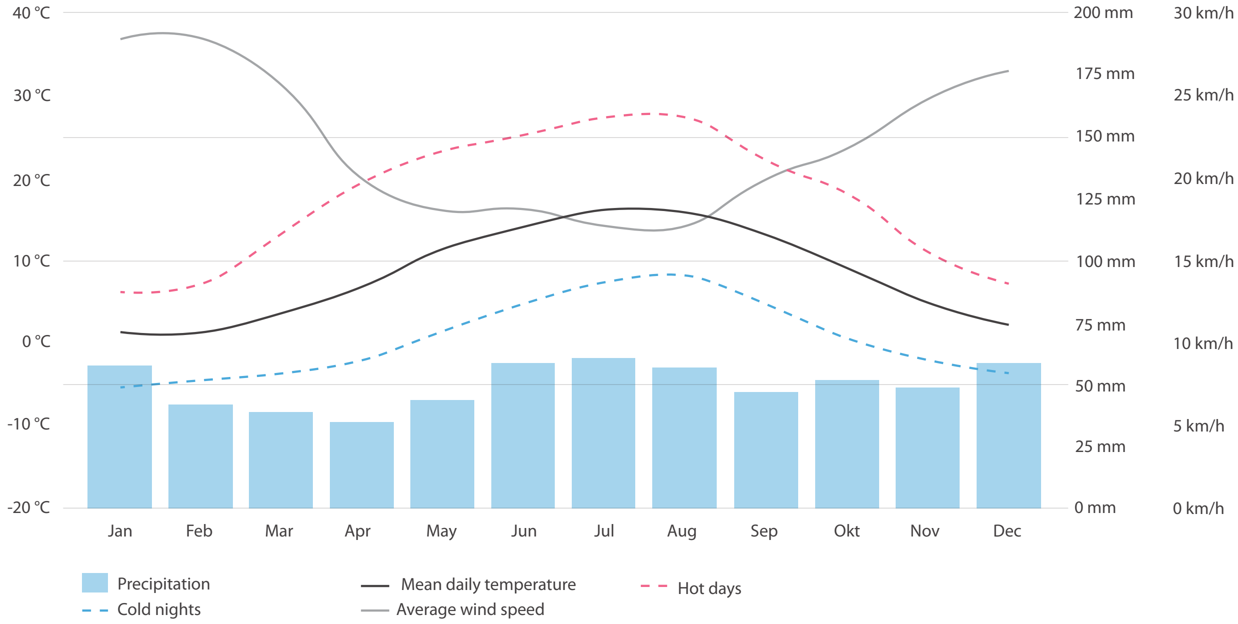


Illustration 4. Average temperature, wind, and precipitation Högnäs, Sweden. (Adapted from Meteoblue, 2022e).

Cold climate and its challenges

Challenges

Wind and precipitation

On their own, wind and precipitation are not significant challenges for earth buildings, as they quite easily can be solved. In combination, however, erosion on earth buildings significantly increases. Wind can give raindrops more kinetic energy, resulting in the raindrops causing more erosion. The degree of erosion depends on the angle at which the rain hits the wall, the amount of rain and the size of the raindrops (Luo et al., 2020).

In a study where samples from demolished rammed earth buildings from Fujian Tulou, a World Heritage Site, were used to test and understand the effect of wind-driven rain (Luo et al., 2020). Rain simulation tests and drip tests were conducted to see the relationship between erosion depth and rain direction. Fujian is located near the coast of southeast China, and during the spring and summer, the area can expect to have more than 20 days of rain per month. In August, the maximum average monthly precipitation peaks at around 275 mm of rain (Luo et al., 2020). Due to the tropical marine climate, the area is prone to abundant rainfall and even typhoons. Rammed earth that is exposed to rain alone can easily be protected by a roof overhang. In wind-driven rain, however, roof overhangs will hardly protect the structural integrity of rammed earth walls (Luo et al., 2020). In the tests, three different types of rammed earth were tested, built at different times and with a different distribution of clay, silt, and sand. The tests showed that the maximum degree of erosion is reached when it rains at an angle of 15°-30° (Luo et al., 2020). This means that earth erodes more when rain acts in combination with the wind.

In Höganäs, there is on average 600 mm of precipitation annually (Meteoblue, 2022e|). Compared to other areas in the same climate in Europe, this amount of precipitation is not considered a lot. The amount and speed of the wind, however, are significant compared to other areas of the same climate in Europe. At the location on the west coast of Sweden, it is quite exposed to wind, in contrast with many areas in Europe which are more protected by land and mountains. This could mean that exposed earth in Höganäs would require more protection against the weather than in other places with significantly less wind.

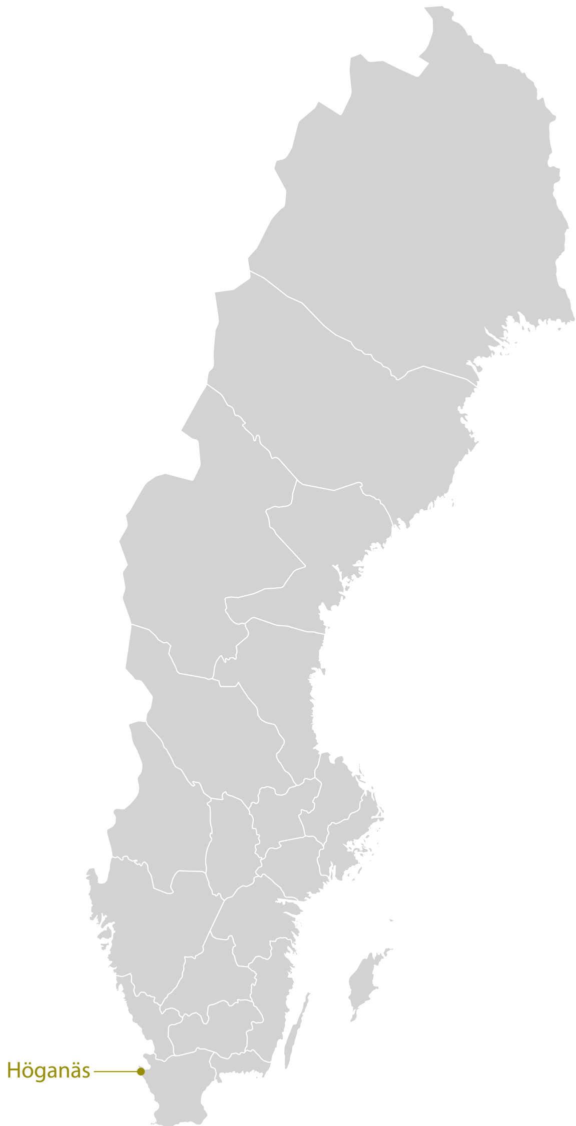


Illustration 4b. Map showing location of Höganäs.

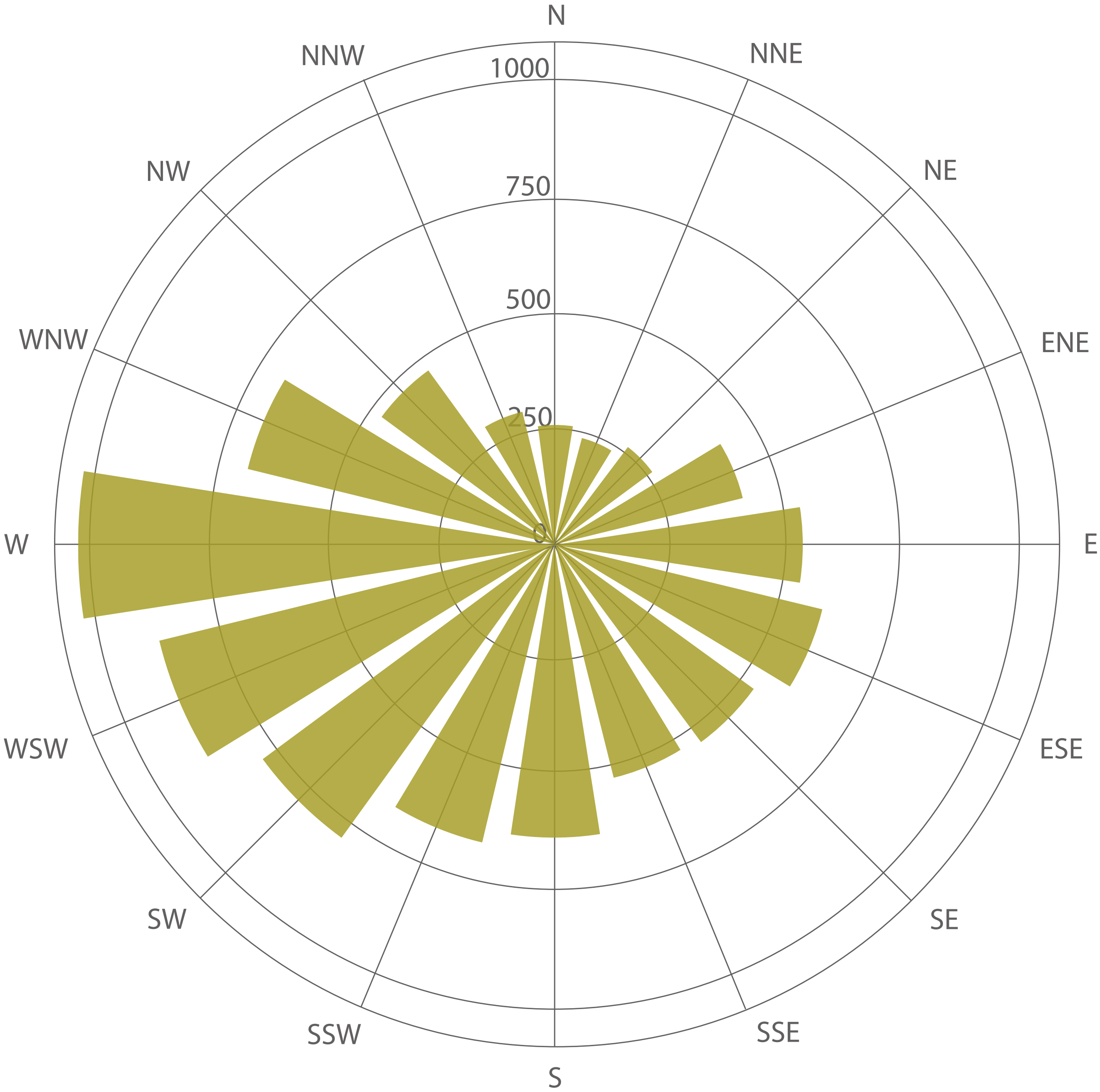


Illustration 5. Wind rose for Höganäs, Sweden showing annual hours of wind. (Adapted from Meteoblue, 2022e).

Earth in a cold climate: Material

Erosion

Effect of weather on earth

Erosion is the process where the forces of wind, precipitation, and frost wear away earthen materials. There are many ways to avoid or slow down erosion on an earth building. A study has been done on the durability of rammed earth, both stabilised and unstabilised, exposed to natural weathering in a wet continental climate with about 1000 mm annual precipitation for 20 years (Bui et al., 2009). There were made 36 rammed earth walls which were rammed into a formwork with the dimensions 1000 mm x 400 mm x 1100 mm on top of a concrete base, with a bituminous layer in between, to protect the walls against the capillary rise. On top of the walls, there was a small roof with an overhang of around 1/15 of the wall height, to simulate an average roof overhang (Bui et al., 2009).

After the 20 years, the erosion of the walls showed that the top part of the walls was less eroded than the rest because the roof had shielded the earth from rain, thereby hindering erosion in that area (Bui et al., 2009). It was also visible that the top of each rammed earth layer, where the earth had been more compacted, had eroded less than the less compacted bottom. The result also showed a significant difference between stabilised and unstabilised rammed earth where the unstabilised rammed earth walls' mean erosion depth was about 6,4 mm (1,6% of wall thickness), while for a rammed earth wall stabilised with 5% of hydraulic lime the mean erosion was about 2 mm (0,5% of wall thickness) (Bui et al., 2009).

The study gives several implications on measures that can be taken to lower erosion on rammed earth walls in a wet continental climate. Having a roof overhang will protect parts of a wall from direct exposure to rain and therefore lower the erosion. A longer roof overhang, compared to wall height, will protect more than a shorter one. Stabilising the rammed earth will slow the erosion significantly, compared to unstabilised rammed earth.

Lastly, the study discusses that while industrial building materials have limited tolerance for erosion because of their mechanical performance, the case for rammed earth is different. Traditional load bearing unstabilised rammed earth walls are usually made of around 50 cm in thickness. Compared to the load they are stressed with at the bottom, the walls are over-dimensioned by a safety factor of between 3 to 10 (Bui et al., 2009). These rammed earth walls could be eroded by 10% and still have a safety factor of 2,7. However, occupants will accept only 5% erosion, due to aesthetical reasons. If the erosion followed a linear function, that means that the walls investigated in the study could erode for over 60 years before they reach the 5% erosion limit (Bui et al., 2009). The nature of erosion is not linear, but rather significant in the very beginning and then decreases to a lower level once the outermost exposed layer has eroded away. This indicated that the actual lifetime of a rammed earth wall would probably be much longer than the linear function suggests (Bui et al., 2009).

An application of a surface treatment can make the earth harder and more water repellent. To do this plasters, paints, linseed oil or lime-washed are examples of what could be applied to achieve this. One option is to apply an extra layer of protection from the weather only on areas the most exposed to rain and wind.

Calculated erosion

Calculated erosion is a used to describe the process of anticipating and counting in erosion before building a rammed earth wall, a name given by Martin Rauch, a modern forerunner in unstabilised rammed earth building in Europe today. Since earth is soluble in water, the surface of earth walls needs to be protected from precipitation, primarily rainfall. When water flows on the surface, small particles are swept away, causing erosion. The faster the water runs along the surface, the more erosion.

Rammed earth is built with clay, sand, and larger aggregates, and as a newly built rammed earth wall is exposed to water the outermost fine layer of mostly clay and sand will be washed away by rain first (Rauch, 2015). After some time, the larger aggregate is uncovered and because they are better and deeper attached to the wall the erosion decreases. As the surface becomes rougher, caused by the exposed larger aggregates, the flow of water is slowed down, also decreasing the erosion (Rauch, 2015). The smaller particles in between the larger aggregates will swell in contact with water, ensuring that water does not penetrate longer into the wall. If the walls are built 2-3 cm thicker than what is necessary, the initial heavy erosion will lead to the wall will reach the initially thought thickness within a few years (Rauch, 2015).

To slow down the flow of water erosion checks can be integrated into the façade. Erosion checks can be made of burned clay tiles, stones, or trass-lime and should be placed or rammed into the wall every 40 to 60 cm throughout the height of the wall (Rauch, 2015). Stones and tiles will protrude from the surface, a present element of the design being visible from several angles and casting shadows. Trass-lime checks, on the other hand, in more integrated into the design as they are flushed with the surface, only differencing in colour against the rest of the surface. Over time, as the surface erodes, the trass-lime checks will start to slightly protrude from the wall (Rauch, 2015).

All though the total erosion of a wall is impossible to know for certain before being built, by estimating and adding estimated erosion thickness to the built wall thickness, the erosion will not be a structural problem. By adding erosion checks to rammed earth walls, the erosion is slowed down, prolonging the lifetime of the wall.

Erosion is the process where the forces of wind, precipitation, and frost wear away earthen materials. Earth buildings can be protected against rain by having for example a relatively long roof overhang. An application of a surface treatments or a stabiliser can protect the surface of an earth building. By increasing the earth walls thickness with the calculated erosion thickness, the erosion does not impact the structural integrity of a wall beyond what is acceptable. Adding erosion checks to the wall will slow the erosion down. In rammed earth walls, the erosion will naturally decrease, and by having a high safety factor to a wall, erosion is not necessarily problematic for the function of the wall.

In the redesign of the rowhouse in Höganäs, the earth should be protected by direct contact with water. This could be done by having a surface treatment or a large roof overhang. If the façade is made with untreated earth, the erosion should be calculated, and the façade should have erosion checks.

Criteria:

- +1 earth is protected from direct contact with water (ex. long roof overhang protects earth from rain)
- +1 surface treatment to strengthen durability or make it water-repellent
- +1 calculated erosion (building a wall thicker by calculating how much will erode)
- +1 erosion checks

(The two lower criteria are only relevant if the façade is made out of raw earth without a surface treatment)

Building envelope moisture control

Shrinkage and cracks

Earth is a water-soluble material, and therefore water is the most significant concern in an earth building over time. When the water is not allowed within the material and dries out quickly enough, earth buildings last a longer time than when water is allowed within. Water can enter earth through cracks on the surface. Cracks are created during the drying of earth, as the material shrinks. The degree of shrinkage can depend on several factors; what kind of clay is used, the ratio of clay, sand and gravel, and how fast it dries.

As a building material, it is a significant disadvantage that earth will swell when in contact with water and shrink when drying. Swelling will only occur if earth is in direct contact with water, humidity in the air will not cause swelling (Minke, 2012).

There are several ways to avoid or reduce shrinkage significantly. In earth, the component that causes shrinking is the clay (Minke, 2012). By adding more sand and larger aggregates, like gravel, the shrinking will be decreased. In a clayey loam mix, the linear shrinkage can be lowered from 5% with 0% sand content, to 0% with 90% sand (Minke, 2012). By adding cut straw, or other organic fibres like bamboo fibres or animal hairs, the shrinkage can also be reduced significantly. Adding a mineral stabiliser will also decrease the shrinkage. Examples of such are cement, lime, and soda waterglass.

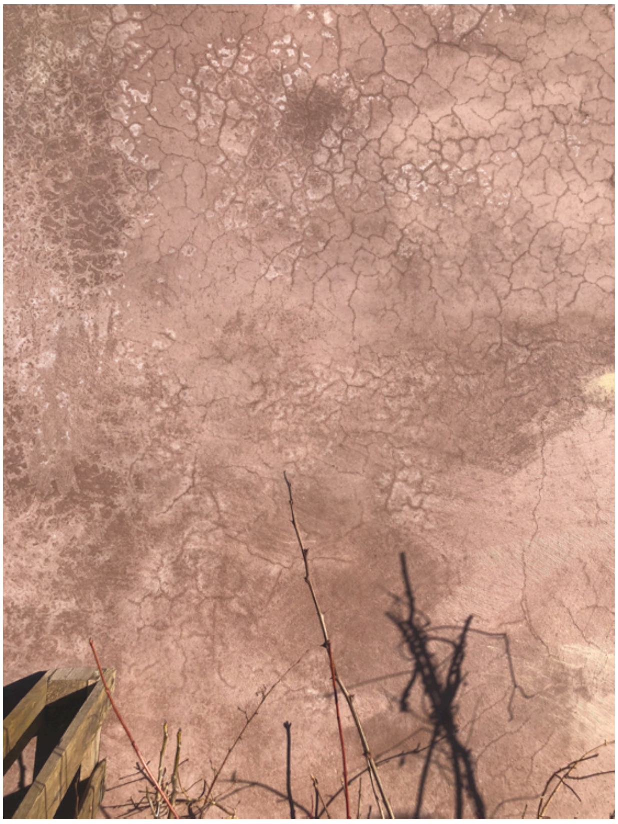
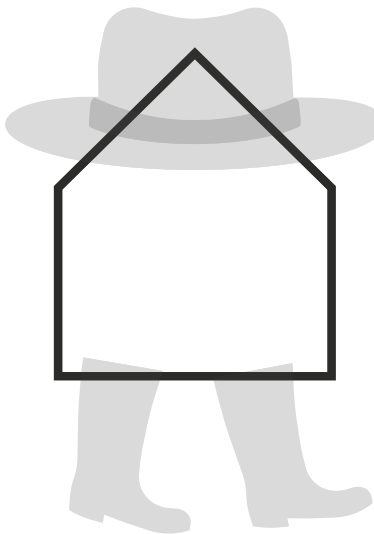


Illustration 6. Image showing cracks in clay plaster facade. Photo: Klara Moene-Omholt.



A good hat and boot

Earth is a water-soluble material. When used in buildings, earth must therefore be protected from direct contact with water. It is said that an earth building needs “a good hat and boots” (Rauch, 2015). The hat, meaning the roof, should be formed in a way that leads water away and prevents it from penetrating into the structure. A solution to this can be a relatively large roof overhang, but not necessarily. Most importantly is a solution that drains rain away and makes sure that no rainwater can collect (Rauch, 2015).

Earth should also be protected from water at ground level. This is both to protect the earth from splashing water when rain hits the ground or other horizontal planes like balconies (Rauch, 2015). Earth also needs to be protected from moisture sucked up in the construction by capillary action. Earth can therefore not be used alone in foundations or plinths. Foundations made of concrete are often used in earth buildings (Rauch, 2015). At the edge between the earth and the foundation, it is necessary to make a slight overhang of the earth with a drip cap to avoid leading water between the earth and the foundation.

Shrinkage can cause cracks in an earth surface. With cracks, water can more easily access the material, lowering its lifetime and increasing the need for maintenance. By having enough sand, gravel, or larger aggregates, essentially lowering the clay content, the earth will shrink less. Adding organic fibres or mineral stabilisers shrinkage will also decrease significantly. Water needs to be lead away from the earth both at the roof and the foundation, a good hat, and a good boot.
In the redesign of the rowhouse in Höganäs, the façade should consist of a blend of materials in which significant shrinkage is not expected. The house should have such a construction, so that water is lead away quickly and does not stay in direct contact with earth for a longer period of time.

Criteria:
+1 aggerates or other additions in earth mixture to prevent shrinkage (and formation of cracks)
+1 “good hat”
+1 “good boot”

Earth in a cold climate: Comfort

Thermal mass

Thermal mass describes a building's ability to store heat. A high thermal mass will keep the inside temperature less influenced by fluctuating outside temperatures, also called thermal inertia. In areas with warmer days and colder nights, thermal mass will absorb heat during the day, and release it during the night. For a building to utilise thermal inertia, thermal mass needs to be on the inside of the insulation layer.

When designing a building, thermal inertia could be used to its advantage as a passive heat source in cold climates. Using the warmth of the sun as a source of heat can replace the need for other heat sources, saving both energy and costs. In a house built close to Alingsås, outside of Gothenburg, an internal wall of rammed earth is located in the centre of the house facing a large south-facing window. This way, the heat from the sun will warm up the rammed earth wall during the day and release it as the temperature drops for the night. Because of the distance between the wall and the window and the height of the window, the sun only reaches the wall in the wintertime when the sun sits low and there is a need for extra heat. In the summer, when the sun sits higher in the sky, the rammed earth wall stays in the shadow, and stays cool.

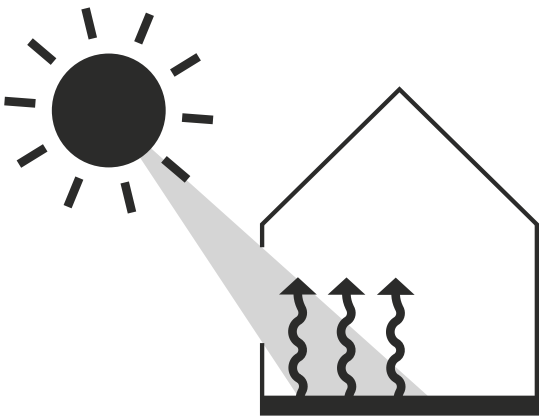
The effect of thermal mass is shown in temperature readings taken in two houses in Cairo, Egypt, in 1964. Two equal volume buildings, one of 50 cm thick earth walls and mud brick vaults, and one with 10 cm thick pre-cast concrete elements and a flat roof (Minke, 2012). During the day the outside temperature fluctuated with about 13°C. In the earth house, the temperature variation was 4°C. In the concrete house the variation of temperature was 16°C, four times higher temperature variation than in the earth house, and well outside the comfort zone in Cairo (Minke, 2012). The reason why the temperature inside the earth house was significantly less influenced by the outside temperatures, is "time lag", which refers to the period of time before the thermal energy from the outside reaches the interior and has an influence on the inside temperature (Minke, 2012).

Thermal mass is a building's ability to store heat. Buildings made of compacted earth have a high thermal mass, and this can be used in cold climates to absorb heat during the day that will be released when the temperature drops. Earth with a high thermal mass will keep indoor temperatures from fluctuating at the same speed as the outside temperature because of "time lag".

In the redesign of the rowhouse in Höganäs, there should be a layer of earth on the inside of the insulations, thick enough to build up some thermal mass. If possible, the earth should be placed in such a way, that it will be directly heated up by the sun during daytime in the winter.

Criteria:

- +1 significant amount of earth on inside of insulation layer
- +1 active use as a heat battery



Earth in a cold climate: Comfort

Cold climate insulation

In cold climates, there is a need for more insulation than in warmer climates to keep be able to keep the warmth within the building from escaping. The thermal insulation of a rammed earth wall is about the same as for a wall of baked bricks (Minke, 2012). Air trapped in porous materials has an insulating effect. The lighter the earth mixture, the better the insulating effect. Moisture content will also influence the thermal insulation, where more moisture will have a negative impact on the insulating effect (Minke, 2012).

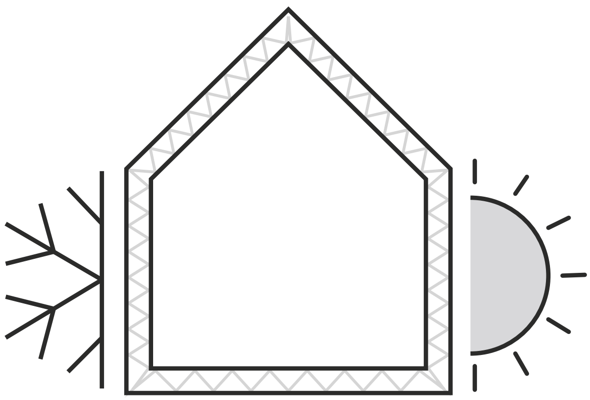
The heat transfer coefficient U (W/m^2K) describes the flow of heat through a building element. Several measures could be done to lower the U-value and thereby increase the insulation effect. To increase the thermal insulation of earth, porous materials can be added to the mixture. Examples of this can be straw, cork, hemp, and other light plant-based materials (Minke, 2012). Porous mineral particles like lava, pumice, foam glass and expanded clay can be used to achieve the same effect (Minke, 2012). The lighter and more porous the earth mix is, the better the insulating effect.

An alternative to mixing porous materials in the earth mix to increase the thermal insulation is to make a separate layer of insulating material. This could be straw-bale, expanded glass, mineral wool, and lightweight organic fibres. Either way, it is important that the insulating material chosen does not hinder vapour diffusion, as this can cause moisture to stay trapped within the building element (Minke, 2012). The insulative layer can be placed on either side of the earth wall or between two earth layers, like a sandwich element.

To insulate for a cold climate when building with earth, added insulation is necessary to keep warm. This can be done by mixing porous materials into the earth. Another possibility is to add a separate layer of insulation.

In the redesign of the rowhouse in Höganäs, there should be either a separate layer of insulation or enough porous material mixed into the earth mix to create a U-value which is satisfactory according to the building regulations. The insulation material should be organic, to not break with the sustainable profile of the house, and should not be hindering vapour diffusion.

Criteria:
- +1 separate layer of insulation (/addition of porous material in earth)
- +1 insulation material should not hinder vapour diffusion
- +1 insulation material should be organic and sustainable (to match the sustainable properties of earth)



Advantages and challenges

Criteria

The complete list

Embedded energy:
- +1 no cement in earth
- +1 building mainly consist of earth or other low embedded energy materials
- +1 use of locally excavated earth

Recyclability:
- +1 raw earth with no stabilisers
- +1 no surface treatment that is hard to remove

Relative humidity regulation:
- +1 raw earth with no stabilisers
- +1 no non-earthen or water-repellent surface treatments
- +1 if earth is the primary inside surface material

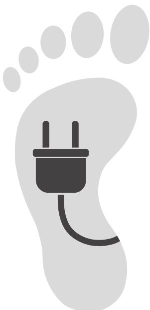
Erosion:
- +1 earth is protected from direct contact with water
- +1 surface treatment to strengthen durability or make it water-repellent
- +1 calculated erosion (building a wall thicker by calculating how much will erode)
- +1 erosion checks

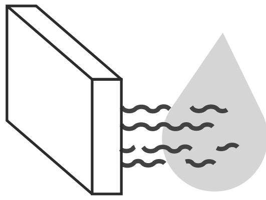
(The two lower criteria are only relevant if the façade is made out of raw earth without a surface treatment)

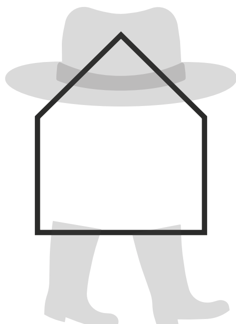
Building envelope moisture control:
- +1 aggerates or other additions in earth mixture to prevent shrinkage
- +1 “good hat”
- +1 “good boot”

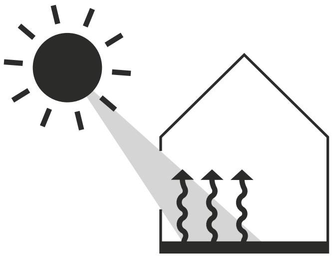
Thermal mass:
- +1 significant amount of earth on inside of insulation layer
- +1 active use as a heat battery

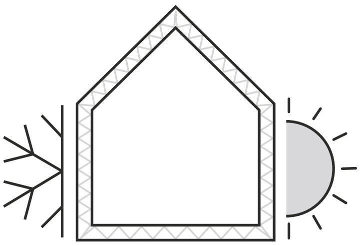
Cold climate insulation:
- +1 separate layer of insulation / addition of porous material in earth
- +1 insulation material should be organic and sustainable












Earth in practice

Reference projects and climates

Introduction

In the following chapter, "Earth in practise", built earth buildings in Europe are studied. First, nine reference project, as well as their location and climate, are studied. The goal is to collect different earth solutions and techniques as well as identify similarities and differences depending on the climate. The location of these nine projects can be seen in the map of Central Europe on the right side of this spread. In the right low corner of this page, a colour explanation of the climates is found. In the following four spreads, the nine reference projects are shortly presented as well as their climate and local climatic conditions. On the first spread, the climate of Höganäs, is shown, and used to compare the climates of the other nine sites to. A comparison of reference projects and climates is made, and results are presented along seen tendencies between earth buildings in the different climates. These will act as strategies for the redesign of the rowhouse in Höganäs.

To further understand and evaluate earth buildings, a closer look at three of the references projects is carried out as case studies. The three case studies are chosen as they have the most similar scale and function to the rowhouse that will be redesigned, out of the nine reference projects. The three projects are built using different styles and techniques which will be evaluated. The evaluation is done using the criteria created from the theory of building with earth. This is done to see how well the respective combination of materials and techniques performs within the categories according to the criteria. Afterward, a discussion of the results from the criteria follows. A discussion of the availability in Sweden follows lastly in each case study and includes qualities, challenges, and possible adaptations. This will be a starting point to the redesign of the rowhouse in Höganäs.

Temperate, no dry season, warm summer (Cfb)
Temperate, no dry season, cold summer (Cfc)
Cold, no dry season, hot summer (Dfa)
Cold, no dry season, warm summer (Dfb)
Cold, no dry season, cold summer (Dfc)
Polar, tundra (ET)

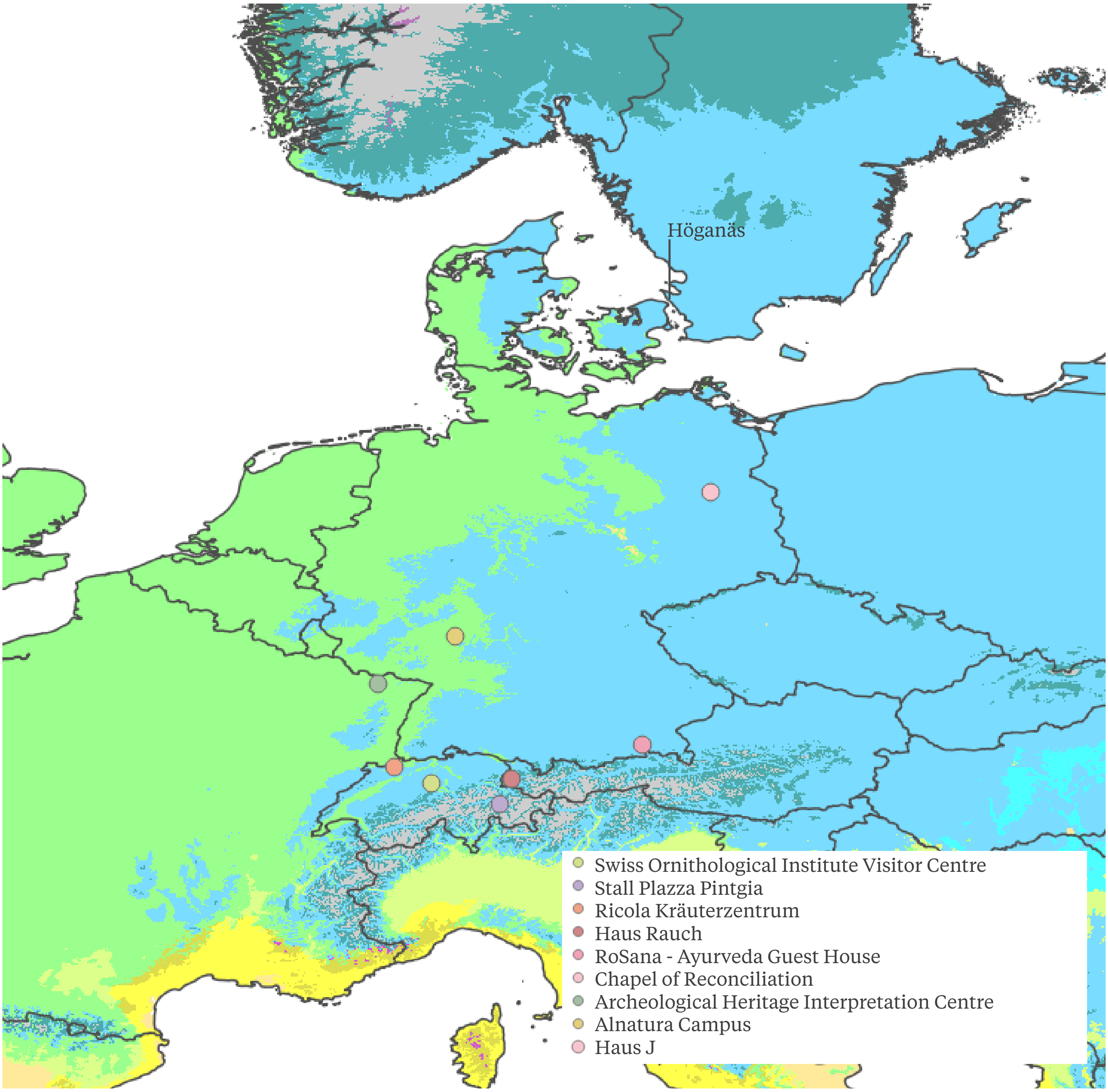
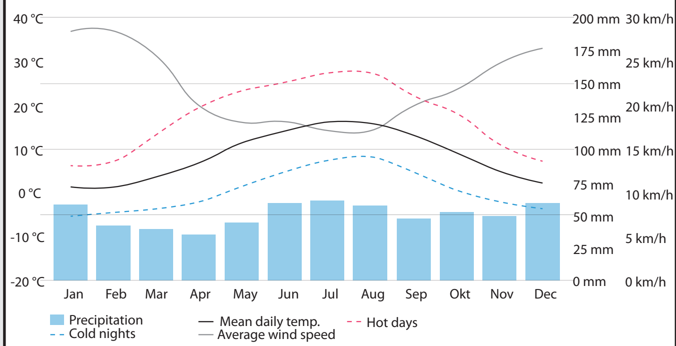


Illustration 7. Map showing climates in Central Europe. (Adapted from (Beck et al., 2018).

Reference projects

Name	Höganäs reference
Picture	
Location	
Year	
Architect	
Usage	
Earth technique	
Load bearing structure	
Earthen work	
Climate	Dfb - cold, no dry season, warm summer
Annual precipitation (mm)	602
Annual precipitation compared to Höganäs	100%
Average wind speed (km/h)	22,33
Avarage wind speed compared to Högnäs	100%
Weather protection	
Average temperature, wind and precipitation	
	Illustration 10. Climate data of Höganäs. (Adapted from Meteoblue, 2022e).

Haus Rauch	Alnatura Campus
	
Illustration 8. Image of Haus Rauch. Photo: Beat Bühler.	Illustration 9. Image of Alnatura Campus. Photo: Tobias Helmersson
Schlins, Austria	Darmstadt, Germany
2008	2019
Roger Boltshauser, Martin Rauch	Haas Cook Zemmrich
Private home	Office building
Rammed earth (unstabilised, in-situ), clay plaster	Rammed earth (unstabilised, pre-fabricated)
Earth	Concrete (earth is self bearing)
Lehm Ton Erde Baukunst GmbH	Lehm Ton Erde Baukunst GmbH
(Source: Heringer, et al., 2019)	(Source: Heringer, et al., 2019)
Cfb - temperate, no dry season, warm summer	Cfb - temperate, no dry season, warm summer
1244	520
207%	86%
9,58	15,75
43%	71%
Erosion checks	Erosion checks

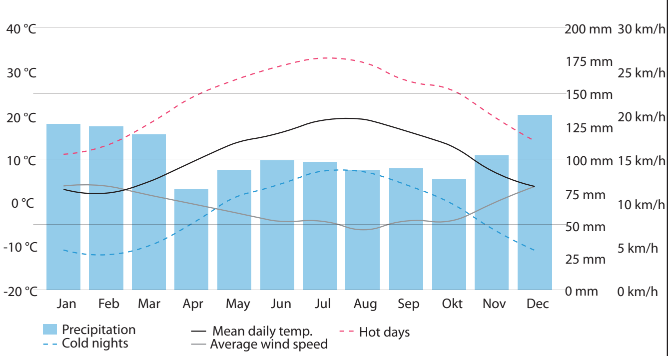
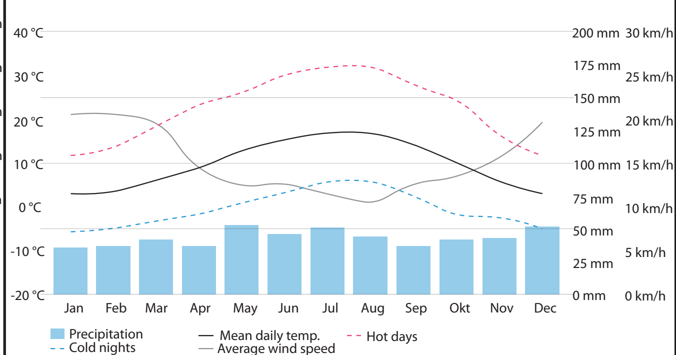
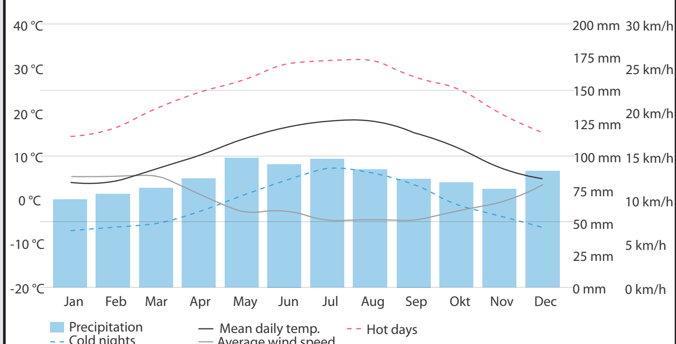

	

Illustration 11. Climate data of Schlins. (Adapted from Meteoblue, 2022h).	Illustration 12. Climate data Darmstadt. (Adapted from Meteoblue, 2022c).

Reference projects

Name	Ricola Kräuterzentrum
Picture	
	Illustration 13. Image of Ricola Kräuterzentrum. Photo: Iwan Baan.
Location	Laufen, Switzerland
Year	2014
Architect	Herzog & de Meuron
Usage	Factory / warehouse
Earth technique	Rammed earth (unstabilised, pre-fabricated
Load bearing structure	Concrete (earth is self bearing)
Earthen work	Lehm Ton Erde Baukunst GmbH
	(Source: Heringer, et al., 2019)
Climate	Cfb - temperate, no dry season, warm summer
Annual precipitation (mm)	1005
Annual precipitation compared to Höganäs	167%
Average wind speed (km/h)	10,25
Avarage wind speed compared to Högnäs	46%
Weather protection	Erosion checks
Average temperature, wind and precipitation	
	Illustration 16. Climate data of Laufen. (Adapted from Meteoblue, 2022f).

Haus J	Archaeological Heritage Interpretation Centre

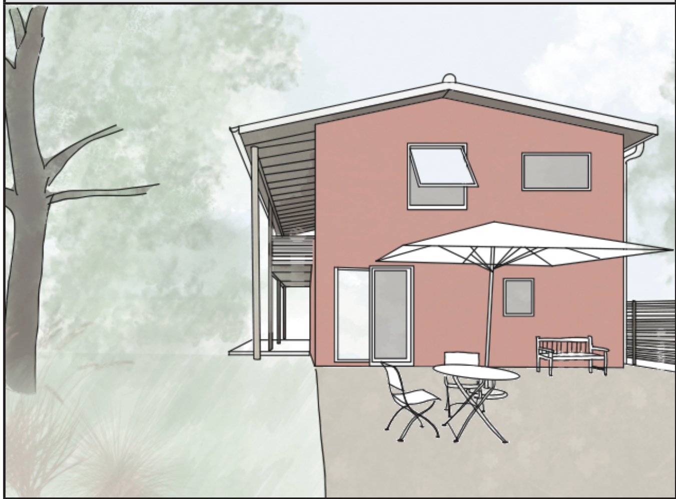



Illustration 14. Image of Haus J. Adapted from photo by Thomas Ott.	Illustrattion 15. Image of AHIC. Photo: Luc Boegly
Darmstadt, Germany	Dehlingen, France
2012	2014
Schauer + Volhard Architekten BDA	Nunc Architectes
Private home	Visitor Centre
Wattle and daub, CEB	Rammed earth (unstabilised, pre-fabricated & in-situ), wattle and daub
Wood	Earth
Unger GmbH & KG	Caracol and Gargano (rammed earth walls), Bisceglia for Rauscher with students from the INSA Strasbourg (wattle and daub)
(Source: Brueggemann, 2014)	(Source: Nunc Architectes, 2022)
Cfb - temperate, no dry season, warm summer	Cfb - temperate, no dry season, warm summer
520	735
86%	122%
15,75	16,08
71%	72%
Clay plaster, roof overhang	Glass facade, roof overhang, surface treatment

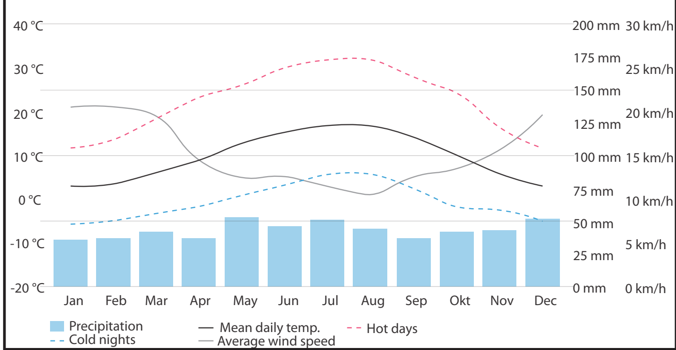
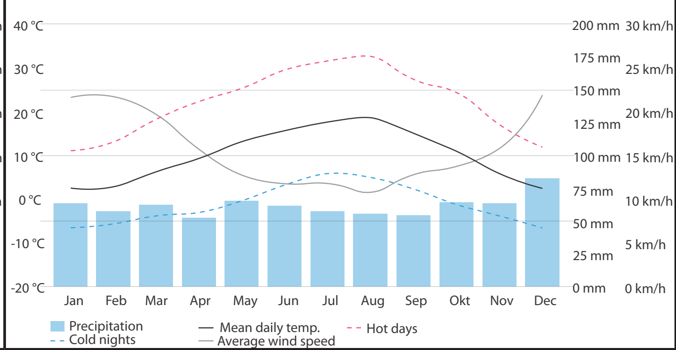
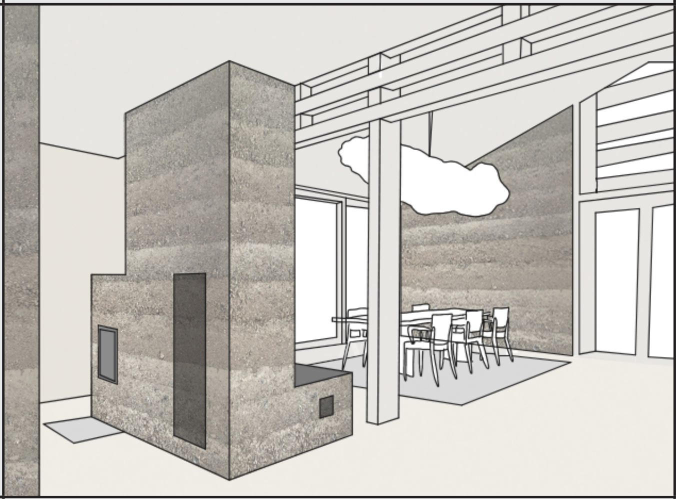
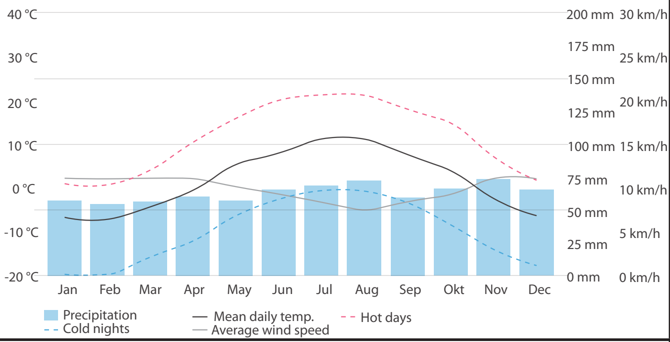

	

Illustration 17. Climate data Darmstadt. (Adapted from Meteoblue, 2022c).	Illustration 18. Climate data Dehlingen. (Adapted from Meteoblue, 2022d).

Reference projects

Name	Stall Plazza Pintgia
Picture	
	Illustration 19. Image of SPP. Adapted from photo by Ralph Feiner.
Location	Almens, Switzerland
Year	2010
Architect	M. Guljan + C. Pally
Usage	Private home
Earth technique	Rammed earth (unstabilised, pre-fabricated)
Load bearing structure	Wood (self bearing earth)
Earthen work	Lehm Ton Erde Baukunst GmbH
	(Source: Erden, n.d.)
Climate	Dfb - cold, no dry season, warm summer
Annual precipitation (mm)	752
Annual precipitation compared to Höganäs	125%
Average wind speed (km/h)	9,75
Avarage wind speed compared to Högnäs	44%
Weather protection	Wood / stone facade (no exposed earth)
Average temperature, wind and precipitation	
	Illustration 22. Climate data of Almens. (Adapted from Meteoblue, 2022a).

Swiss Ornithological Institute Visitor Centre	Chapel of Reconciliation
	
Illustration 20. Image of SOIVC. Photo: Tobias Helmersson.	Illustration 21. Image of Chapel of Reconciliation. Photo: Reinhard Görner.
Sempach, Switzerland	Berlin, Germany
2014	2000
:mlzd Architekten	Rudolf Reitermann, Peter Sassenroth
Visitor Centre	Chapel
Rammed earth (unstabilised, pre-fabricated)	Rammed earth (unstabilised, in-situ)
Earth	Earth
Lehm Ton Erde Baukunst GmbH	Lehm Ton Erde Baukunst GmbH
(Source: ArchDaily, 2015)	(Source: Erden.at, n.d.)
Dfb - cold, no dry season, warm summer	Dfb - cold, no dry season, warm summer
1801	511
299%	85%
9,75	19,75
44%	88%
Erosion checks	Wood outer facade (no directly exposed earth)

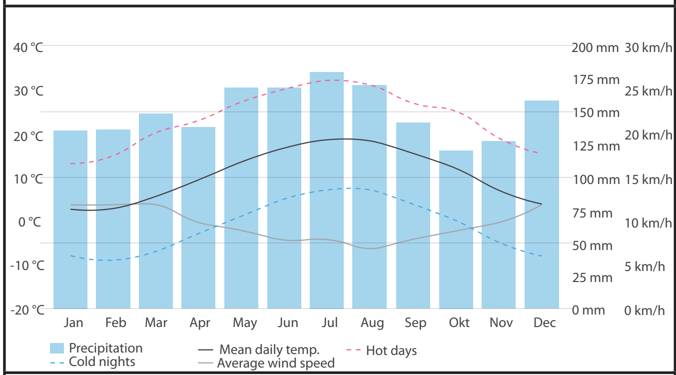
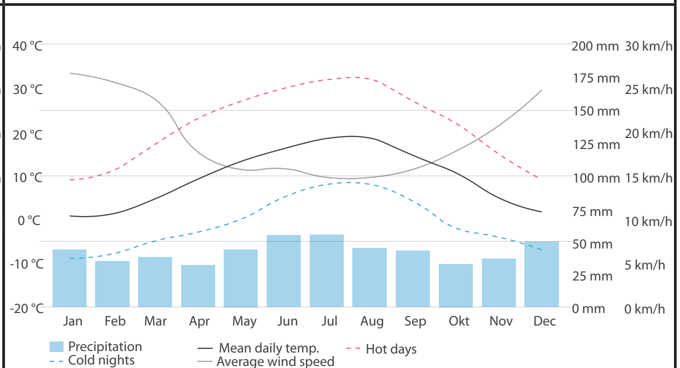
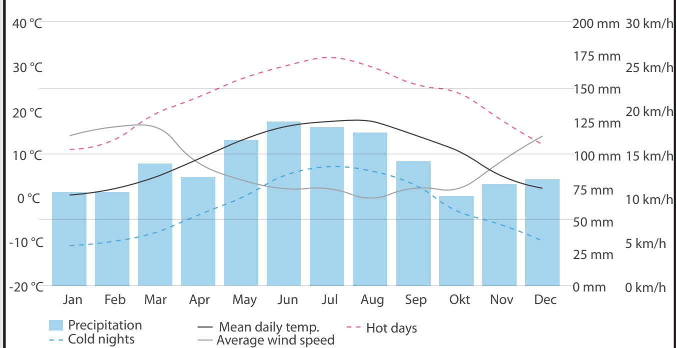

	

Illustration 23. Climate data of Sempach. (Adapted from Meteoblue, 2022i).	Illustration 24. Climate data of Berlin. (Adapted from Meteoblue, 2022b).

Reference projects

Name	RoSana - Ayurveda Guest House
Picture	
	Illustration 25. Image of RoSana. Photo: Gabrijela Obert
Location	Rosenheim, Germany
Year	2021
Architect	Studio Anna Heringer, Lehm Ton Erde
Usage	Guest House
Earth technique	Rammed earth (unstabilised, pre-fabricated), clay plaster
Load bearing structure	Wood (self bearing earth)
Earthen work	Lehm Ton Erde Baukunst GmbH
	(Source: Studio Anna Heringer, 2021)
Climate	Dfb - cold, no dry season, warm summer
Annual precipitation (mm)	1106
Annual precipitation compared to Höganäs	184%
Average wind speed (km/h)	13,67
Avarage wind speed compared to Högnäs	61%
Weather protection	Wood facade (no exposed earth)
Average temperature, wind and precipitation	
	Illustration 26. Climate data Rosenheim. (Adapted from Meteoblue, 2022g).

Reference projects and climates
Evaluation

Climate

Wind:
The wind in Höganäs is the one with the highest average speed (22,3 km/h), which can be explained due to the fact that Höganäs is located on the west coast of Sweden, especially exposed to high wind speeds. Among the locations of the reference projects, the average wind speed is lower which can be expected from locations farther into the inland, protected by mountains and vegetation. The average wind speed in the locations of the reference projects varies from 9,6 km/h to 19,8 km/h and does not seem to have a clear connection to the type of climate.

Precipitation:
The annual average precipitation varies from 511 mm in Berlin (Chapel of Reconciliation) to 1801 mm in Sempach (Swiss Ornithological Institute Visitor Centre), a significant difference. In Höganäs the average annual precipitation is 602 mm. There is no clear connection between the amount of precipitation and climate.

Temperature:
When looking at the average temperatures the difference between cold and temperate climates is clear. The temperature is generally lower in a cold climate than in a temperate climate. In January, the mean daily temperature is 2,8°C lower in the cold climate locations (-0,3°C on average) than at the locations in temperate climates (2,5°C on average). In July the mean daily temperature is 1,8°C higher at the locations in temperate climates (18,3°C on average) than at the locations in cold climates (16,5°C on average).

Summary:
The mapping of the climate of the reference projects and Höganäs shows a broad variety of wind and precipitation. When comparing the climate of the ten sites, of which five are in a temperate climate and five are in a cold climate, there is no clear pattern in the difference in wind speed and average precipitation, the difference then possibly is more related to the surrounding landscape like oceans, mountains, and woods which can influence the weather. However, there is a difference to be seen in the temperatures, where locations in a cold climate will have lower temperatures than locations in a temperate climate.

Illustraion 27. Image rammed earth wall. Photo: Klara Moene-Omholt

Reference projects and solutions

Facades vary from rammed earth to clay renders to wood. It can generally be seen that the reference projects in temperate climates have exposed earth as the façade material, while in cold climates the facades are made of other materials like wood and stone and have the earth in the interior.

Since there is no significant difference in wind speed and precipitation between temperate and cold climates, the difference in the choice of façade material is probably caused by the difference in temperature. With colder temperatures also comes more frost erosion which can be another reason why buildings in cold climates may be less fit to have untreated earth as the outer layer of the façade. It can be seen that in a building like the RoSana Ayurveda Guest House in Rosenheim, a cold climate, has rammed earth walls as inner walls and as the innermost layer of the outer walls, while the façade is made out of wood. This can be a strategy to implement the low embedded energy of earth in a building while protecting the earth from erosion, by having another more durable material on the façade. All expect one of the references projects in a cold climate has a different material than earth as the outermost layer on the façade.

Colder temperatures will require more insulation in the walls, which will make walls in colder climates thicker than walls in temperate climates. Load bearing earth normally needs to have a thickness of around 300 – 500 mm, which will make the total wall thickness with a fitting amount of insulation in a cold climate have a substantial thickness. An example of this can be seen at the Swiss Ornithological Institute Visitor Centre located in Sempach, a cold climate. Here the total wall thickness is 800 mm, 450 mm of which are rammed earth and 320 mm of which are insulation. While this wall thickness may be suitable for larger public buildings, it may be too thick for most smaller and residential buildings. This can be an explanation to why there are not many examples of cavity walls in earth buildings, especially not in residential buildings.

Conclusion:
The difference between the reference projects in the cold climate and the temperate climate can primarily be seen in the choice of façade material. In a cold climate, it can be seen that other materials than earth are used for the façade, like wood and stone, or a surface treatment to make it more water repellent or durable. There can be several reasons for this, and one of them is that as untreated earth is vulnerable to frost erosion, and by having another material than earth as the façade and rather having earth in the interior, the earth is protected from the cold temperatures and frost erosion. If talking about load bearing earth and the thickness of this, in combination with the required thickness of insulation in cold climates, this will add up to a wall thickness that would cause earth cavity walls to not be relevant for most smaller residential buildings.

Illustraion 28. Image rammed earth. Photo: Klara Moene-Omholt

Case studies

Haus Rauch

Introduction

Illustration 29. Image of Haus Rauch. Photo: Beat Bühler.

Name	Haus Rauch
Location	Schlins, Austria
Year	2008
Architect	Roger Boltshauser, Martin Rauch
Usage	Private home
Earth technique	Rammed earth (in-situ, unstabilised), clay plaster
Load bearing structure	Earth
Earthen work	Lehm Ton Erde Baukunst GmbH

(Source: Heringer, et al., 2019).

Haus Rauch is a private home that was built by and for Martin Rauch, the founder of Lehm Ton Erde, and a pioneer in rammed earth buildings in modern Europe. The house is built using excavated earth from the building site itself to make the unstabilised in-situ rammed earth walls. The wall construction consists of 450 mm rammed earth, 100 mm reed mat insulation, and 40 mm clay plaster, outside to inside (Rauch, 2015). The project was built with around 2 cm thicker walls than required as calculated erosion and fired clay tiles as erosion checks to slow down the erosion. For the first couple of years, the façade changed quite a bit as the outermost layers eroded. Martin Rauch has stated that even though he knew the process of erosion, even he could get a bit nervous during several hours of heavy rain (Heringer, Blair Howe, & Rauch, 2019). The house was built as a sort of an experiment and has been a forerunner for many of Rauch's later works.

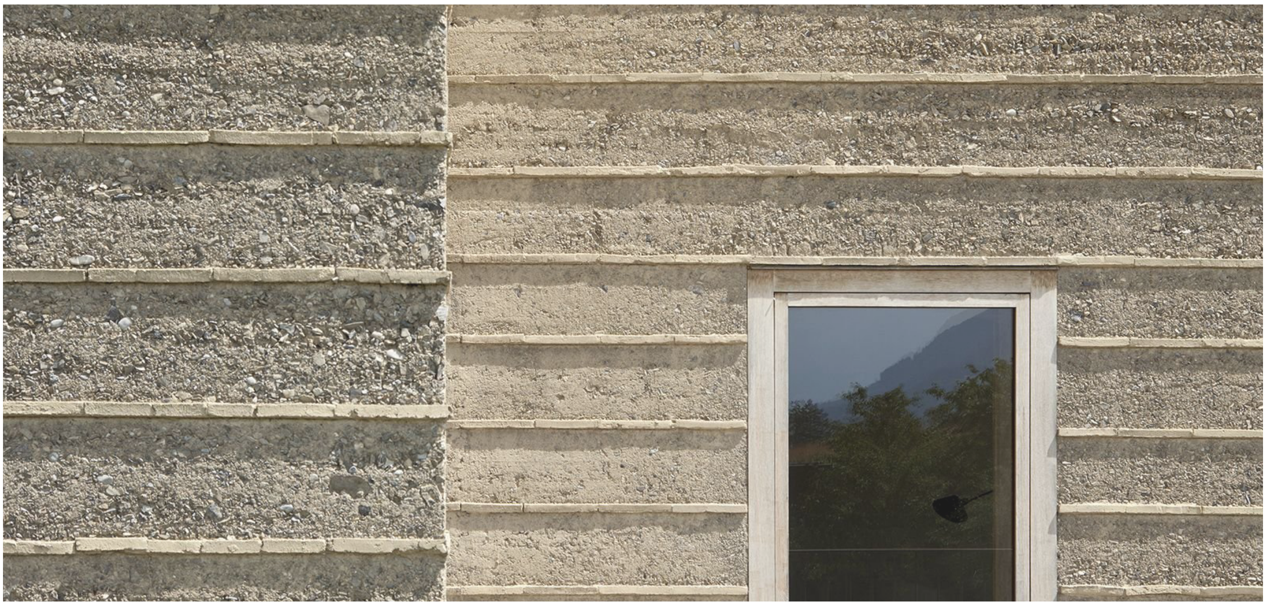


Illustration 30. Image showing erosion checks in Haus Rauch. Photo: Beat Bühler.

Case studies

Haus Rauch

Criteria

Criteria	Haus Rauch
Embedded energy:	3/3
+1 no cement in earth	1
+1 building mainly consist of earth or other low embedded energy materials	1
+1 use of locally excavated earth	1
Recyclability:	2/2
+1 raw earth with no stabilisers	1
+1 no surface treatment that is hard to remove	1
Relative humidity regulation:	3/3
+1 raw earth with no stabilisers	1
+1 no non-earthen or water-repellent surface treatments	1
+1 if earth is the primary inside surface material	1
Building envelope moisture control:	3/3
+1 aggerates or other additions in earth mixture to prevent shrinkage	1
+1 “good hat”	1
+1 “good boot”	1
Erosion:	2/4
+1 earth is protected from direct contact with water	0
+1 surface treatment to strengthen durability or make it water-repellent	0
+1 calculated erosion	1
+1 erosion checks	1
Thermal mass:	1/2
+1 significant amount of earth on inside of insulation layer	1
+1 active use as a heat battery	0
Cold climate insulation:	3/3
+1 separate layer of insulation (/addition of porous material in earth)	1
+1 insulation material should not hinder vapour diffusion	1
+1 insulation material should be organic and sustainable	1
TOTAL:	17/20

Discussion

The Haus Rauch performs well in many categories, according to the criteria. In the categories embedded energy, recyclability, relative humidity regulation and building envelope moisture control Haus Rauch ticks off all points. This indicates that the use of raw rammed earth and clay plaster does a satisfactory performance in achieving this.

All though it ticks off all criteria in cold climate insulation as well, it should be noted that the walls are 600 mm thick and have an estimated U-value of 0,42 W/m²K, which would not the allowed in Sweden. If it was going to be built in Sweden, the U-value would need to be lower, which can easily be done with more insulation, and thereby make the walls even thicker. This may not be relevant for most housing projects in Sweden.

Earth as a façade material sends a strong signal on the sustainability of the house. However, since the earth façade is not directly protected, the house is exposed to erosion. The strategy for this house rather aims for a slowing down of the erosion. This may be a solution that could work when building in Höganäs in Sweden, although the impact of the local wind, precipitation, and salt from the sea it can be difficult to estimate. Another factor is how well erosion in itself is perceived by inhabitants on the coast of Sweden.

The use of earth as an active heat battery can quite easily be implemented, and it is more dependent on the design and plans if it is relevant.

The question of the availability of the respective earth techniques in Sweden is difficult. Clay plaster, being quite similar to other plasters and renders, could suggest that finding qualified manpower for this should be manageable. Rammed earth on the other hand does not have an obvious equivalent and more commonly known building technique. The low number of built rammed earth examples in Europe, none of this scale in Sweden, suggest that it could be rather difficult and rather expensive. However, for those who have sustainability and the indoor environment as their highest priority, it may be possible.

Case studies

Haus J

Introduction

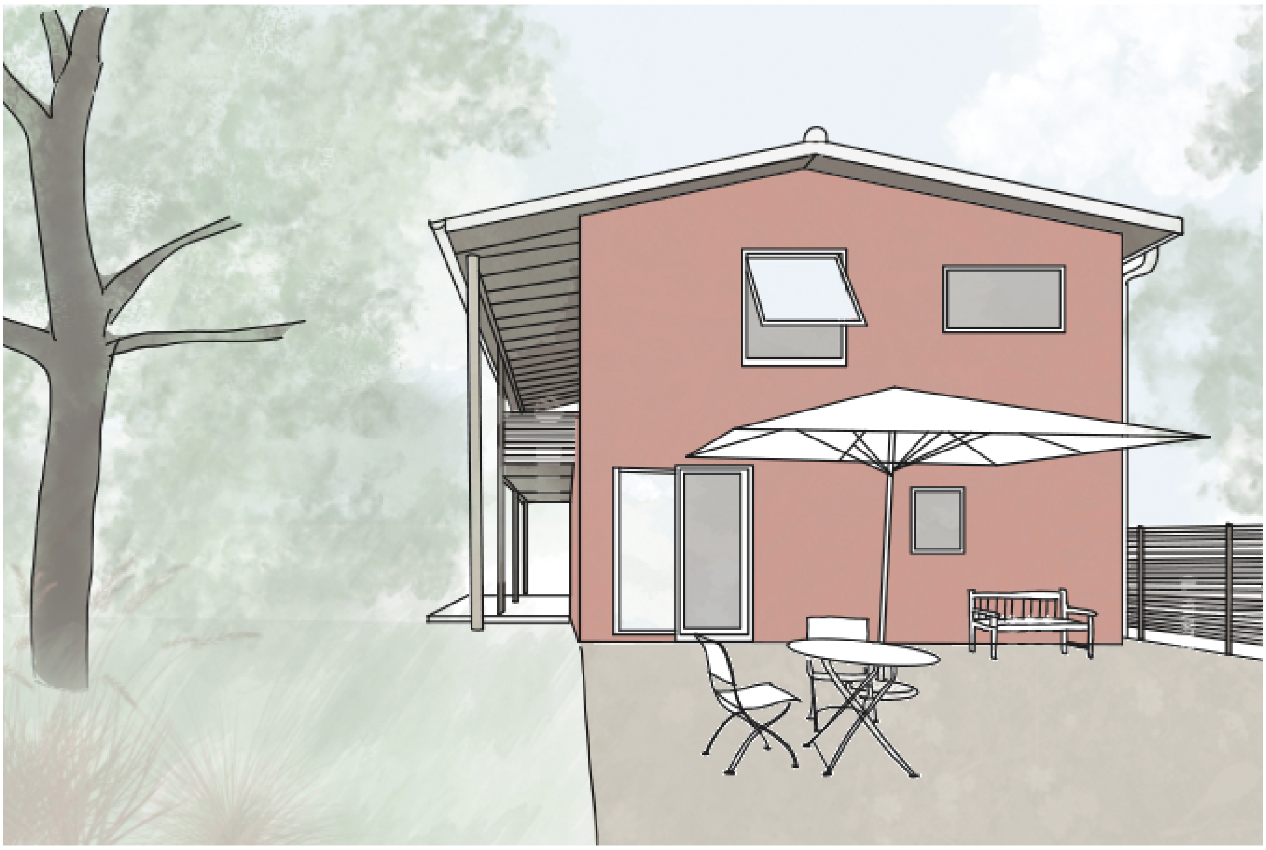


Illustration 31. Image of Haus J. Adapted from photo by Thomas Ott.

Name	Haus J
Location	Darmstadt, Germany
Year	2012
Architect	Schauer + Volhard Architekten BDA
Usage	Private home
Earth technique	Wattle and daub, CEB
Load bearing structure	Wood
Earthen work	Unger Gmbh & KG

(Source: Brueggemann, 2014).

Haus J is a private home built for an older couple in Darmstadt in 2012 and was built trying to minimise waste from the construction. To build up thermal mass, the interior walls are filled with CEBs so that the temperature stays cool in the summer (Schauer + Volhard, n.d.). Outer wall construction is 290 mm thick, and consists of 15 mm gypsum fibre boards, 140 mm loose cellulose insulation (with the wooden structure), 120 mm straw-clay (wattle and daub technique), and 15 mm lime plaster (inside to outside) (Brueggemann, 2014). The estimated U-value is 0,29 W/m²K. The house blends harmoniously into the neighbourhood, and according to Brueggemann (2014): “The special thing about the house is that it doesn’t want to be special: it precisely fulfils the wishes of its residents and radiates beauty and harmony in an unspectacular and natural way”.

Illustration 32. Image of Haus J interior. Adapted from photo by Thomas Ott.

Case studies

Haus J

Criteria

Criteria	Haus J
Embedded energy:	3/3
+1 no cement in earth	1
+1 building mainly consist of earth or other low embedded energy materials	1
+1 use of locally excavated earth	1
Recyclability:	2/2
+1 raw earth with no stabilisers	1
+1 no surface treatment that is hard to remove	1
Relative humidity regulation:	0/3
+1 raw earth with no stabilisers	0
+1 no non-earthen or water-repellent surface treatments	0
+1 if earth is the primary inside surface material	0
Building envelope moisture control:	3/3
+1 aggerates or other additions in earth mixture to prevent shrinkage	1
+1 "good hat"	1
+1 "good boot"	1
Erosion:	2/2
+1 earth is protected from direct contact with water	1
+1 surface treatment to strengthen durability or make it water-repellent	1
~~+1 calculated erosion~~	-
~~+1 erosion checks~~	-
Thermal mass:	1/2
+1 significant amount of earth on inside of insulation layer	1
+1 active use as a heat battery	0
Cold climate insulation:	3/3
+1 separate layer of insulation (/addition of porous material in earth)	1
+1 insulation material should not hinder vapour diffusion	1
+1 insulation material should be organic and sustainable	1
TOTAL:	14/18

Discussion

Haus J performs well in the categories erosion, recyclability, and embedded energy, according to the criteria. The use of earth in wattle and daub with a lime plaster and long roof overhangs provides for this, as both earth and straw in the wattle and daub mixture have a low embedded energy and assuming that the earth is excavated locally. Lime plaster is a durable surface treatment.

The weak point in Haus J, according to the criteria, is the lack of earth on the walls inside the house. By having gypsum fibreboards on all walls indoors, Haus J miss out on the benefits of the indoor climate that earth provides. By switching the gypsum fibreboards to clay boards or adding a clay plaster, Haus J would have a relative humidity regulation inside.

Seen from the outside, Haus J, does not like a special house, due to the lime plaster. This could be both an advantage and a disadvantage. If the goal is to have a house that does not stand out too much, that maybe would be palatable for more people, then a lime plaster is a good choice, as lime plaster is something commonly seen on house facades. If the goal is to have a house made of earth that sends a strong signal on sustainability or ecology to the environment, a lime plaster is not the best solution. Another option is to have a brown colour painted on the lime plaster to mimic the appearance of earth, to keep some of the identity of earth while avoiding the erosion of earth.

The use of earth as an active heat battery can quite easily be implemented, and it is more dependent on the design and plans if it is relevant.

The CEBs on the inside of the inner walls are very similar to regular fired bricks and should be easy to find qualified craftmanship, given that the CEBs themselves are available, in Sweden. The wattle and daub, however, cannot be compared to another known technique that easily. A more available solution would be to replace the wattle and daub with CEBs or adobes. On the other hand, the wattle and daub is not load bearing, and could maybe be done by hand by an earth enthusiastic builder, given that there are no issues with the building regulations if there was a desire to use this technique in Sweden.

Case studies

RoSana – Ayurveda Guest House

Introduction

Illustration 33. Image of RoSana. Photo: Gabrijela Obert.

Name	RoSana – Ayurveda Guest House
Location	Rosenheim, Germany
Year	2021
Architect	StudioAnna Heringer & Lehm Ton Erde
Usage	Guest house
Earth technique	Rammed earth (prefabricated, unstabilised), clay plaster
Load bearing structure	Wood
Earthen work	Lehm Ton Erde Baukunst GmbH

(Source: Wagenstaller & Der Bau, 2021).

RoSana Ayurveda Guest House is located in Rosenheim Germany. The guest house was designed to seek physical and mental stress relief and built to be as healthy for the planet and for the people as possible (Studio Anna Heringer, 2021). The construction of the building is therefore mostly built using natural materials, a solid wood structure, wood and willow as façade material, soft wood fibre boards as insulation, and rammed earth and clay plasters on the interior walls (Wagenstaller & Der Bau, 2021). Next to the building is a small forest, and the building was designed to blend in with its surroundings.

Illustration 34. Image of RoSana interior. Photo: Gabrijela Obert.

Case studies

RoSana – Ayurveda Guest House

Criteria

Criteria	RoSana AGH
Embedded energy:	3/3
+1 no cement in earth	1
+1 building mainly consist of earth or other low embedded energy materials	1
+1 use of locally excavated earth	1
Recyclability:	2/2
+1 raw earth with no stabilisers	1
+1 no surface treatment that is hard to remove	1
Relative humidity regulation:	3/3
+1 raw earth with no stabilisers	1
+1 no non-earthen or water-repellent surface treatments	1
+1 if earth is the primary inside surface material	1
Building envelope moisture control:	3/3
+1 aggerates or other additions in earth mixture to prevent shrinkage	1
+1 “good hat”	1
+1 “good boot”	1
Erosion:	2/2 (4)
+1 earth is protected from direct contact with water	1
+1 surface treatment to strengthen durability or make it water-repellent	1
~~+1 calculated erosion~~	-
~~+1 erosion checks~~	-
Thermal mass:	1/2
+1 significant amount of earth on inside of insulation layer	1
+1 active use as a heat battery	0
Cold climate insulation:	3/3
+1 separate layer of insulation (/addition of porous material in earth)	1
+1 insulation material should not hinder vapour diffusion	1
+1 insulation material should be organic and sustainable	1
TOTAL:	17/18 (20)

Discussion

The RoSana Guest House is built well with earth according to the criteria. Building mostly with the natural materials earth, clay, and wood has proved to be a good choice in the categories embedded energy, recyclability, relative humidity regulation, building envelope moisture control, and cold climate insulation.

Since the earth is not directly exposed to the outside by having a wooden façade, erosion of earth is no longer a challenge. Although wood has a higher embedded energy than earth, it still has a lower embedded energy than many of the alternatives, like concrete and steel. Along the west coast in Sweden where precipitation and heavy winds are a part of the climate, having a more durable and more familiar façade material, as wood is, may be a good solution.

The use of earth as an active heat battery can quite easily be implemented, and it is more dependent on the design and plans if it is relevant.

Rammed earth is not a well-known building technique, especially not in Sweden. There are no familiar building techniques that can be compared to ramming earth, so finding qualified manpower might turn out to be difficult. However, since the rammed earth is not load bearing it lowers the requirements for strength and quality. This means that the rammed earth could be built by someone who has no experience with ramming from before, and examples of this have been seen before. An example of this is the METI School by Anna Heringer in Bangladesh, where local villagers were educated and trained in the technique, building the school (ArchDaily, 2010). Non-load bearing rammed earth could be built in Sweden by people who are willing to spend the time and energy on it, provided that there are no issues with the building regulations. Rammed earth has a unique aesthetical expression, that may be worth going through some extra work for. Clay plaster, on the other hand, is similar to other plasters and renders, and qualified manpower should not be difficult to find. Clay plaster and rammed earth share many of the same qualities regarding embedded energy, recyclability, and relative humidity regulation. Therefore the rammed earth could be replaced by clay plaster if the aesthetical expression is not of great priority.

Case studies

Evaluation

Conclusion

There are many different solutions for building with earth. Prioritising a low embedded energy, minimal erosion, aesthetic expression, availability, a good indoor climate, or other factors will lead to different combinations of material and solutions as the best ones.

These three examples of earth buildings can be said to work with earth in three different ways. Haus Rauch was built with as much of the contrition as possible in earth, and using earth excavated from the site to be as sustainable as possible by keeping the embedded energy low. Haus J was built to be a sustainable house while not costing a fortune, and to harmony with the surrounding houses in the neighbourhood. RoSana was built to be a healthy building for both people and nature. Here the inside walls are made up of earth to benefit the indoor climate, using natural more durable materials on the façade.

If a low embedded energy is the most important, then choosing a solution with as much earth as possible is the right solution. The earth should be load bearing, on the interior walls, and the façade. Examples of this could be load bearing rammed earth or CEBs (compressed earth blocks), with a clay plaster at the opposite side of the wall construction.

If availability is the highest priority, choosing earth building techniques that are similar to other well-known building techniques would be the best solution. Then it could still be possible to build with earth in Sweden, even though earth is not a widespread material or technique. Examples of this could be CEBs, which are similar to fired bricks, and clay plaster, which is similar to other plasters. Choosing a wooden or other commonly used structure would reduce the need for specialists in the structural calculations.

If minimal erosion is the most important priority, then choosing a solution where the earth is protected would be the best solution. This could be done by having a waterproof or durable surface treatment on the façade, although the solution with the least risk of erosion is having another material than earth on the façade. Depending on what is available, examples could be wood or a lime plaster as a façade material, with clay plaster or rammed earth on the interior walls.

These three priorities will set the starting point for the redesign of the rowhouse in Höganäs in the next chapter, as they give three different and possible approaches to work with an earth building design. Adjustments will be made to make the designs fitting for the cold climate of Höganäs.

Illustration 35. Image of clay plaster. Photo: Klara Moene-Omholt.


Design

Design

Rowhouse in Höganäs

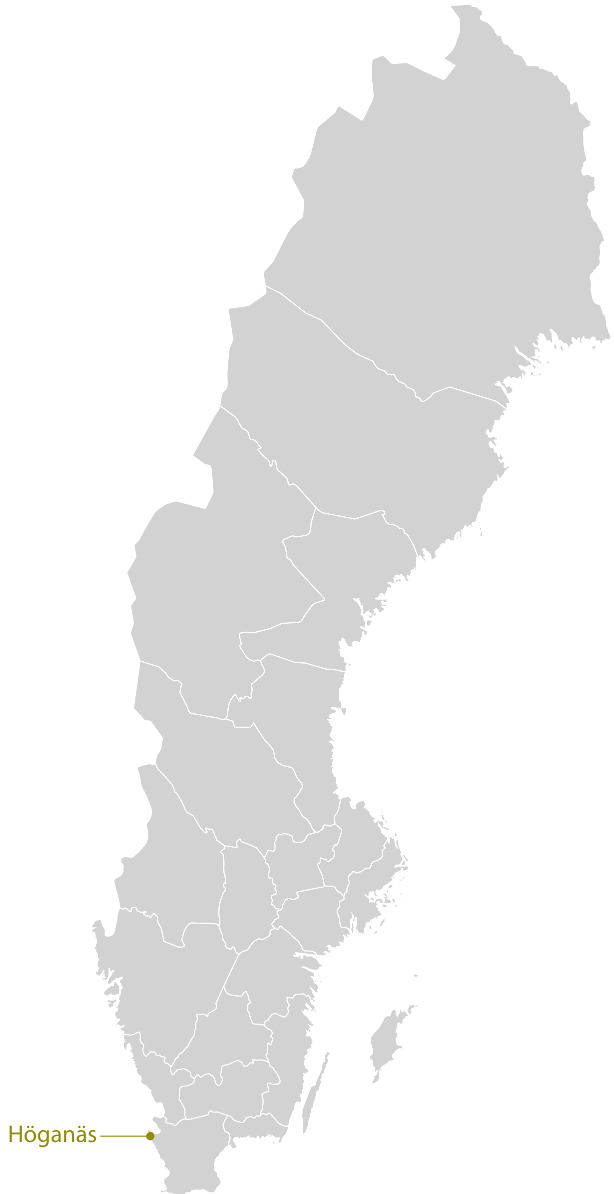
Redesign

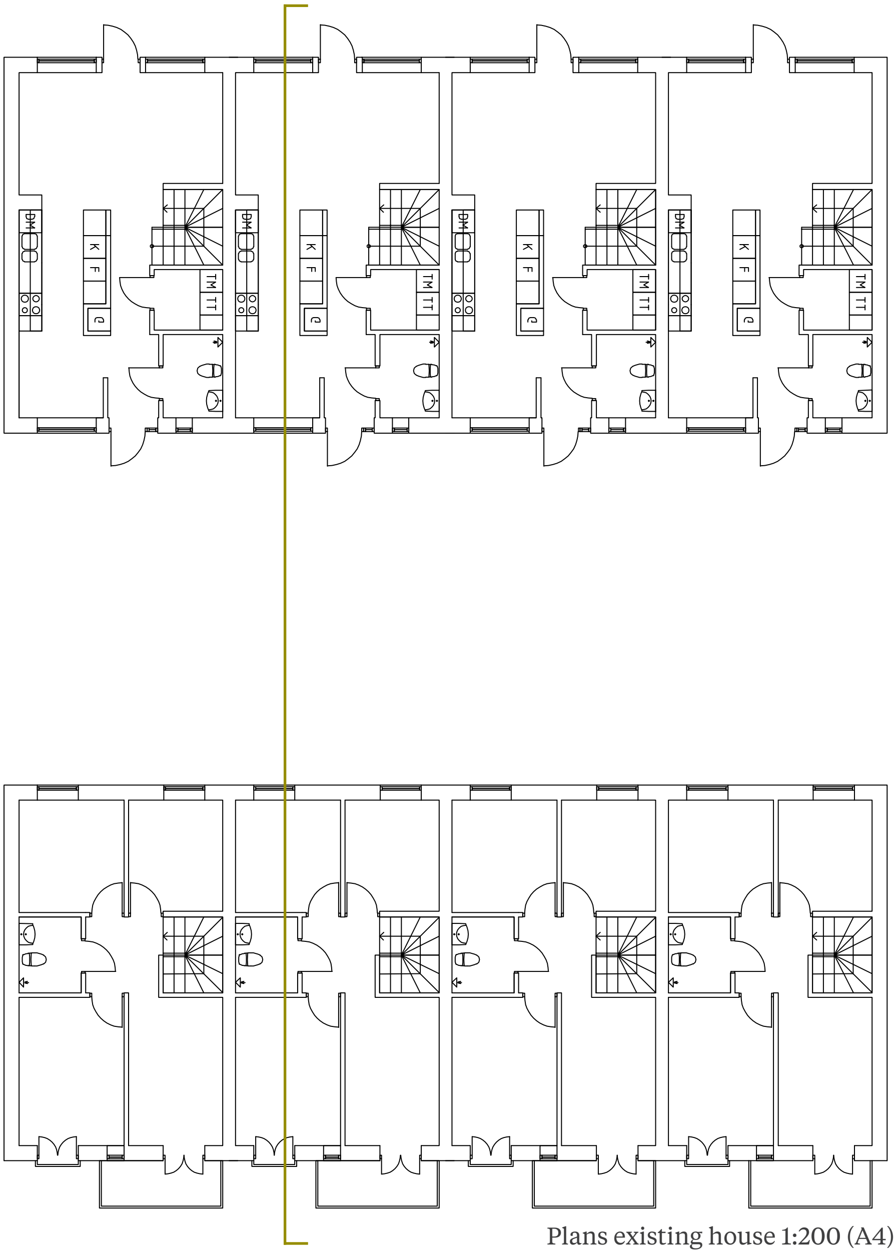
The rowhouse is a building that most people in Sweden are familiar with, whether they have friends or family living in one, or have lived in one themselves. It is therefore a building that is easy to understand and get an overview of. This rowhouse located in Höganäs in Sweden, built in 2018, is chosen because of the aforementioned reason and because of the material choice: concrete with a brick façade.

The build-up of the 400 mm wall construction is not clearified anywhere, and the assumed wall build up is as follows (inside to out):

- 150 mm concrete
- 200 mm insulation
- 20 mm wooden structure
- 30 mm brick tile cladding

Using this starting point, the estimated embedded energy is 342 kWh/m^2.





Plans existing house 1:200 (A4).

Facade existing house 1:200 (A4).

Illustration 36. Plans and facade of rowhouse in Höganäs. (Adapted from GBJ bygg, n.d.).

Redesign
Suggestion 1

Low embedded energy

In the first suggestion the focus was to keep the low embedded energy of earth. This was achieved by having as much of the wall construction as possible in raw earth. The inspiration for this suggestion came from Haus Rauch, using a rammed earth façade with erosion checks, and a thick clay plaster on the interior side, for thermal mass inside the insulation layer.

Wall construction (590 mm), inside to outside:
- 40 mm clay plaster
- 200 mm straw bale insulation
- 350 mm rammed earth (load bearing)

Estimated embedded energy:
- 3,8 kWh/m² (98,9% savings compared to the original design)

Estimated U-value:
- 0,22 W/m²K

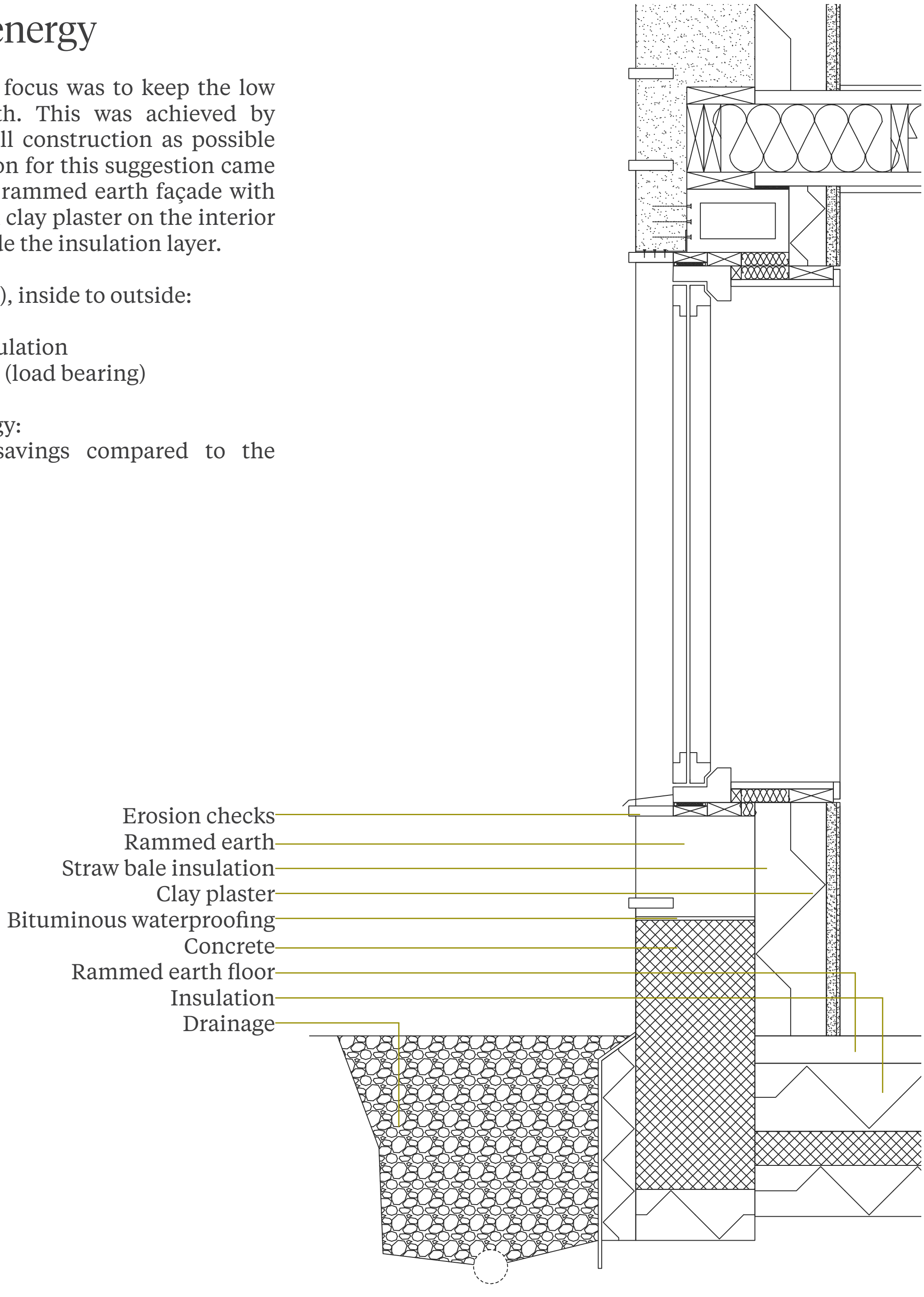


Illustration 37. Detail section 1:20 (A4).

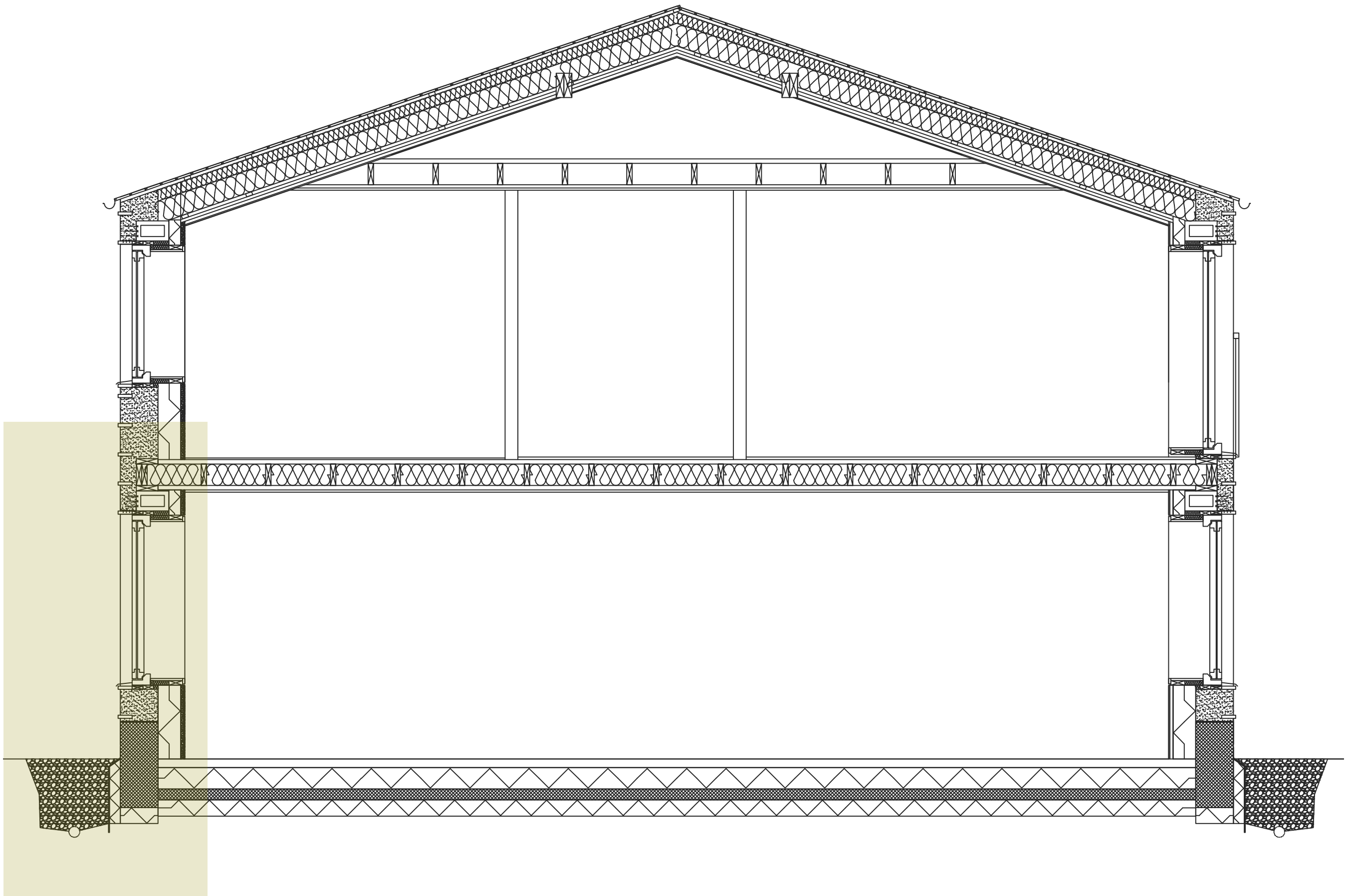


Illustration 38. Section 1:70 (A4).

Redesign

Suggestion 2

Easy and available

In the second suggestions availability was the main priority, and this was achieved by using earth materials and techniques that are similar to commonly used building techniques in Sweden, in order to implement earth into the design, using already available resources. This was accomplished using clay plaster, which is similar to other plaster, and compressed earth blocks (CEB), which is similar to fired bricks. Both the structure and the façade is made of wood, which is a common solution in Sweden. This inspiration for this suggestion was Haus J, where an effort was made to not stand out too much in the surrounding neighbourhood, using sustainable materials, and CEBs inside the wooden structure for thermal mass.

Wall construction (410 mm), inside to outside:

- 20 mm clay plaster
- 110 mm CEB
- 200 mm straw bale insulation (+ wood structure, load bearing)
- Vapour barrier
- 50 mm wooden façade (+ wood structure)

Estimated embedded energy:

- 3,1 kWh/m^2 (99,1% savings compared to the original design)

Estimated U-value:

- 0,23 W/m^{2}K

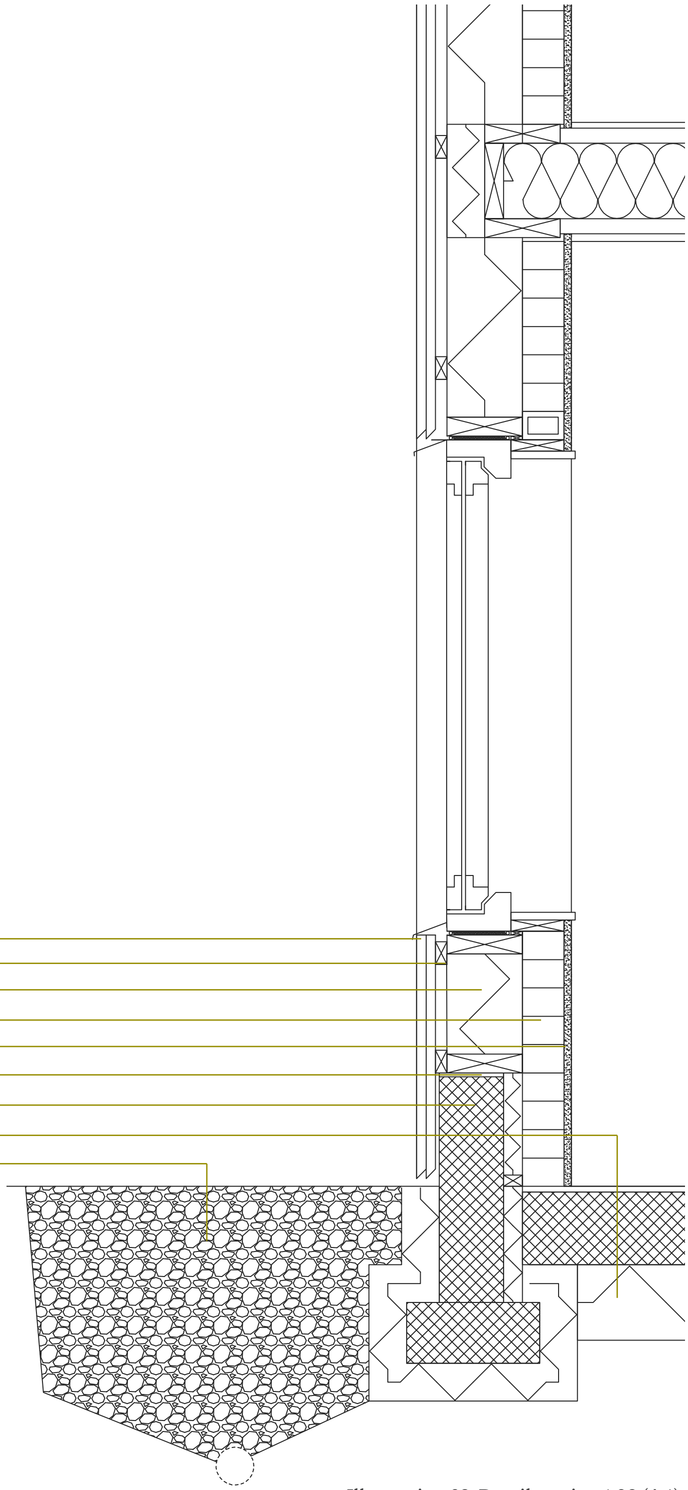


Illustration 39. Detail section 1:20 (A4).

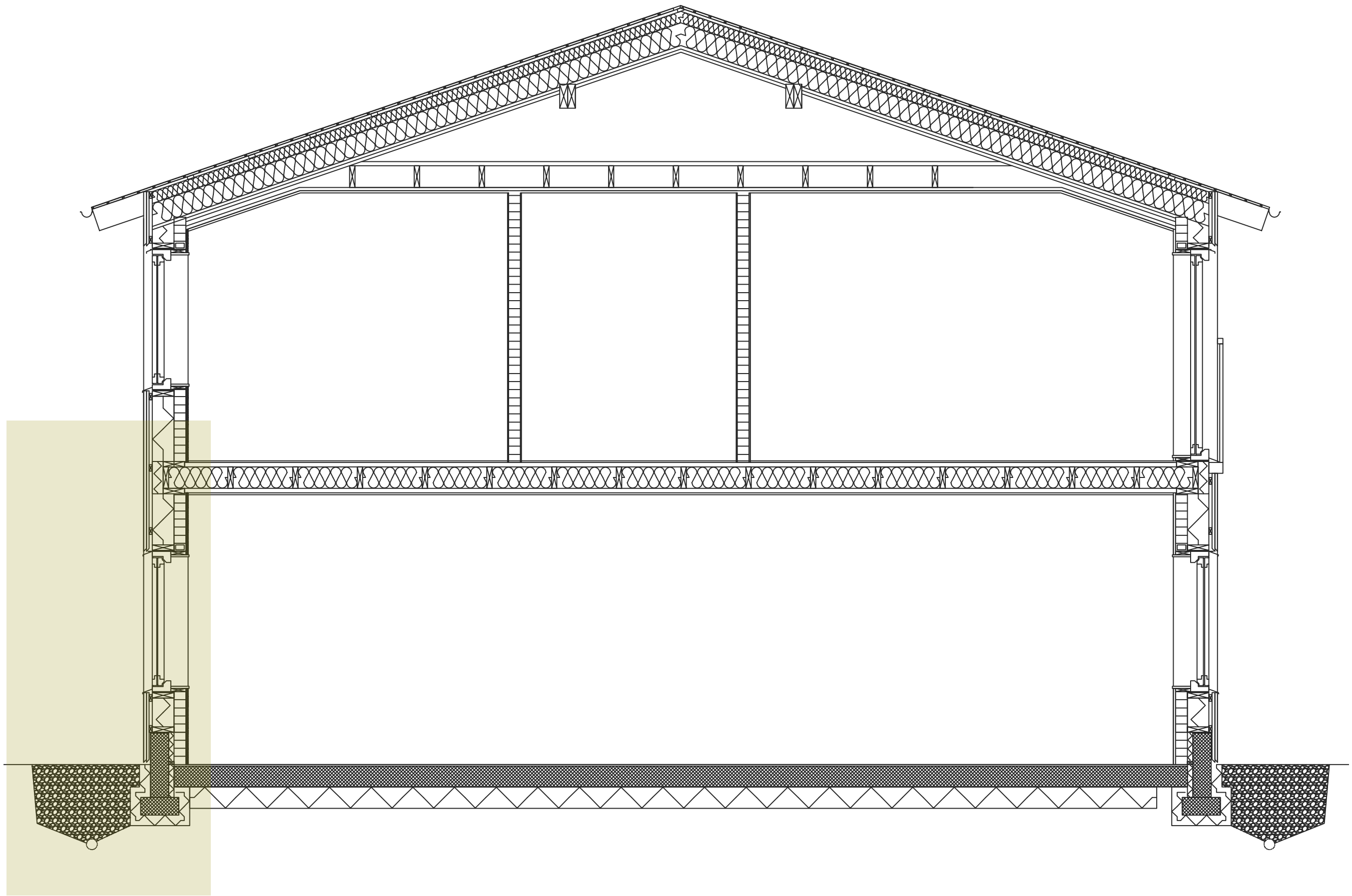


Illustration 40. Section 1:70 (A4).

Redesign

Suggestion 3

Low erosion

In the third suggestion, the focus was to have a low erosion while achieving the benefits of earth inside. This was achieved by using a lime plaster on the façade, which erosion slower than a clay plaster, and rammed earth on the inside to see the unique expression of earth, while also having thermal mass and relative humidity regulation. The inspiration for this suggestion was RoSana, where earth was used on the inside, and a different, more durable material, as the façade.

Wall construction (470 mm), inside to outside:
- 250 mm rammed earth (load bearing)
- 200 mm straw bale insulation
- 20 mm lime

Estimated embedded energy:
- 20,8 kWh/m² (93,9% savings compared to the original design)

Estimated U-value:
- 0,22 W/m²K

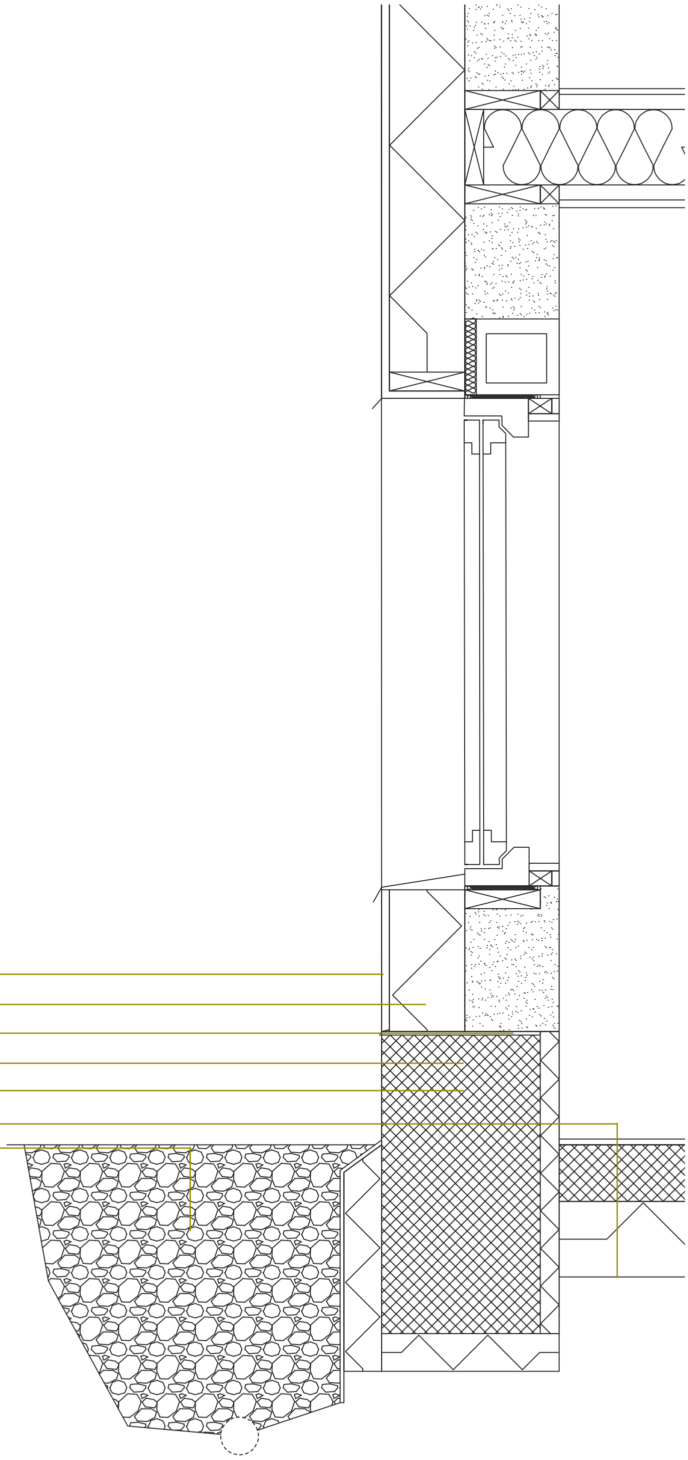


Illustration 41. Detail section 1:20 (A4).

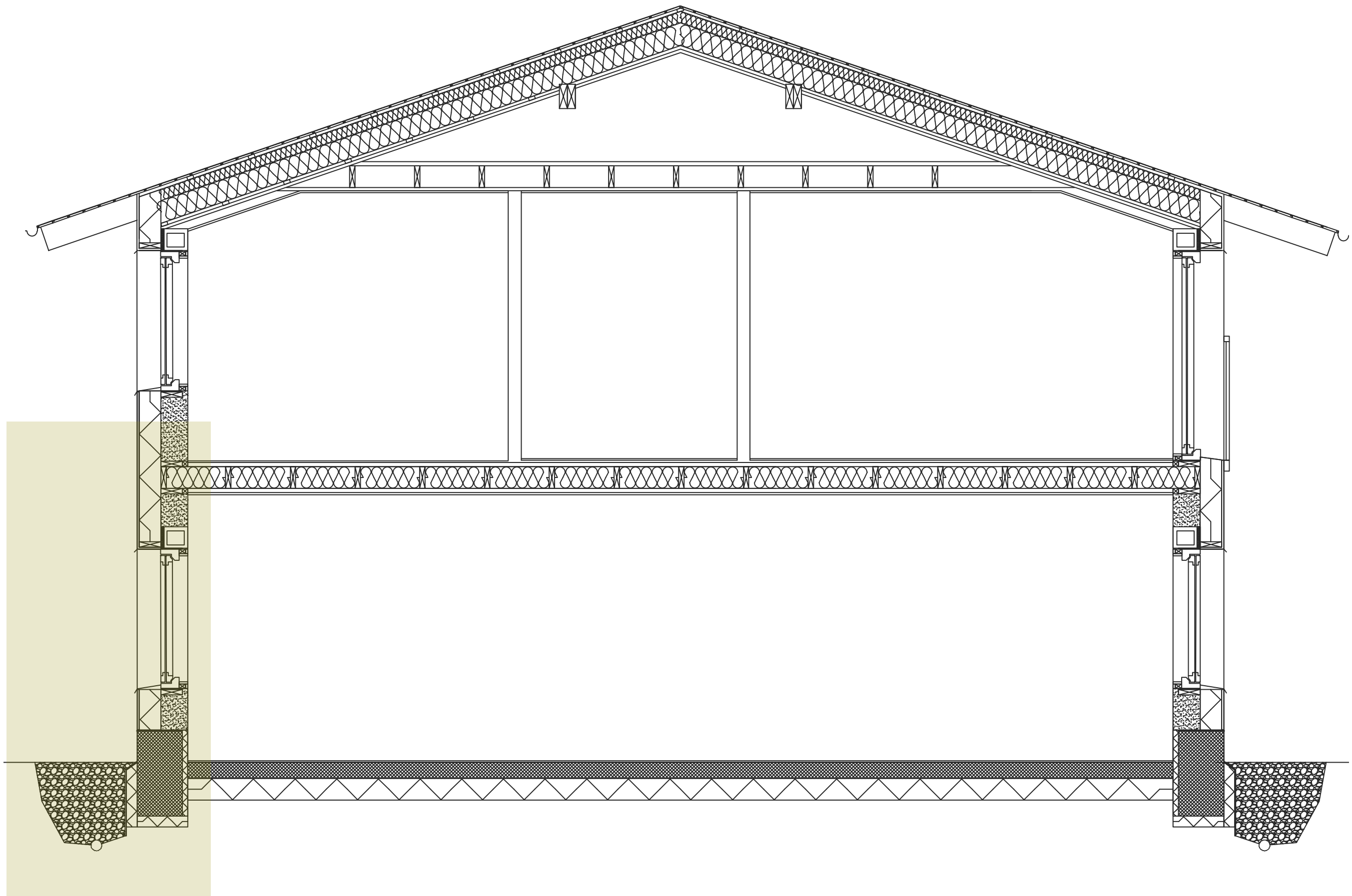


Illustration 42. Section 1:70 (A4).

Redesign

Suggestion 4

Combination

In the fourth suggestion an attempt to combine all the priorities of the previous three suggestion was made. This was achieved by having as much of the wall construction in earth, to keep a low embedded energy, using available earth materials, clay plaster and CEBs, and a more durable material than earth on the façade, lime plaster. The inspiration came from all three of the case studies, and the goal was to see how a suggestion using the best qualities from each priority.

Wall construction (550 mm), inside to outside:
- 20 mm clay plaster
- 300 CEB (load bearing)
- 200 mm straw bale insulation
- 30 mm lime plaster

Estimated embedded energy:
- 30,2 kWh/m² (91,2% savings compared to the original design)

Estimated U-value:
- 0,21 W/m²K

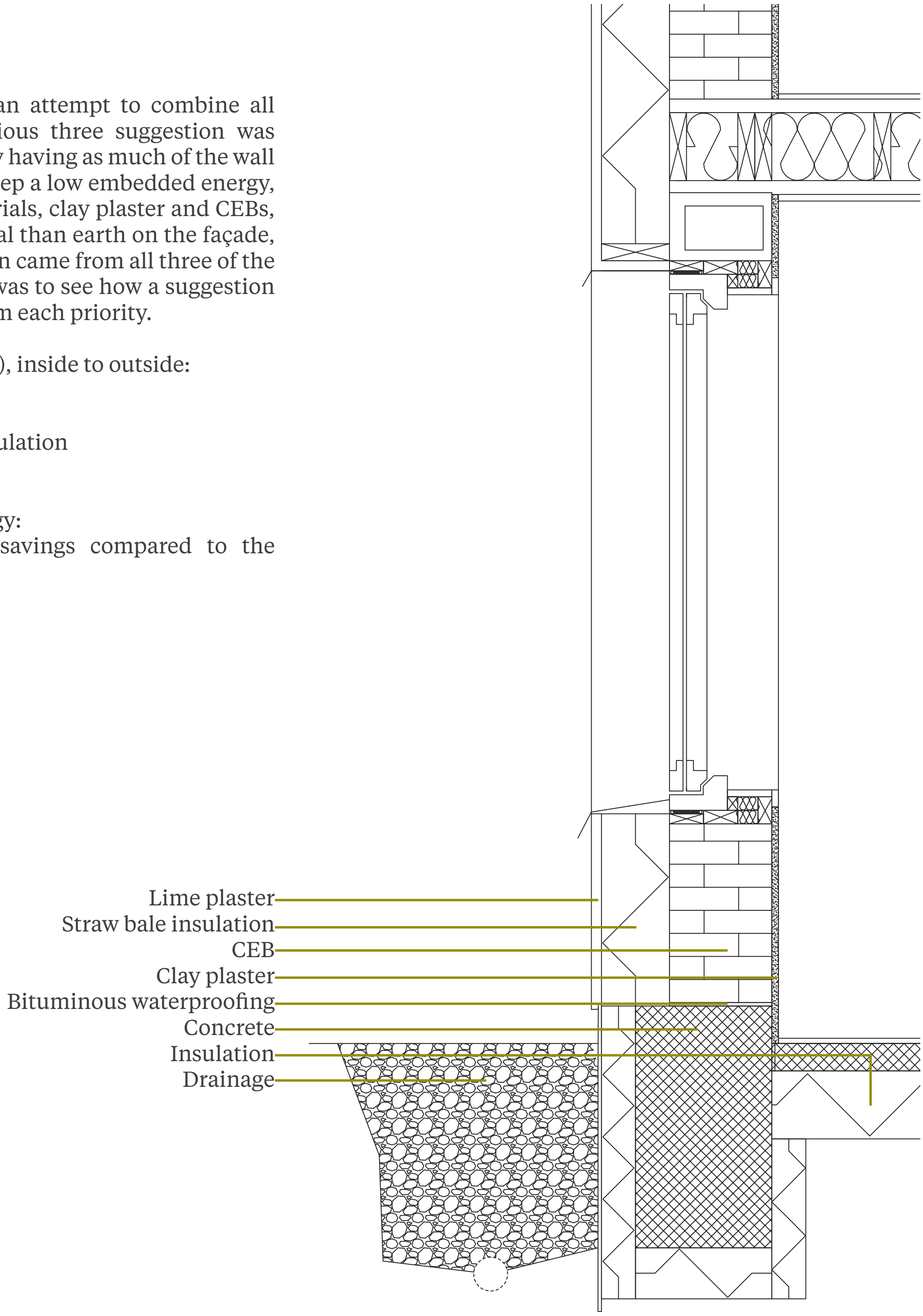


Illustration 43. Detail section 1:20 (A4).

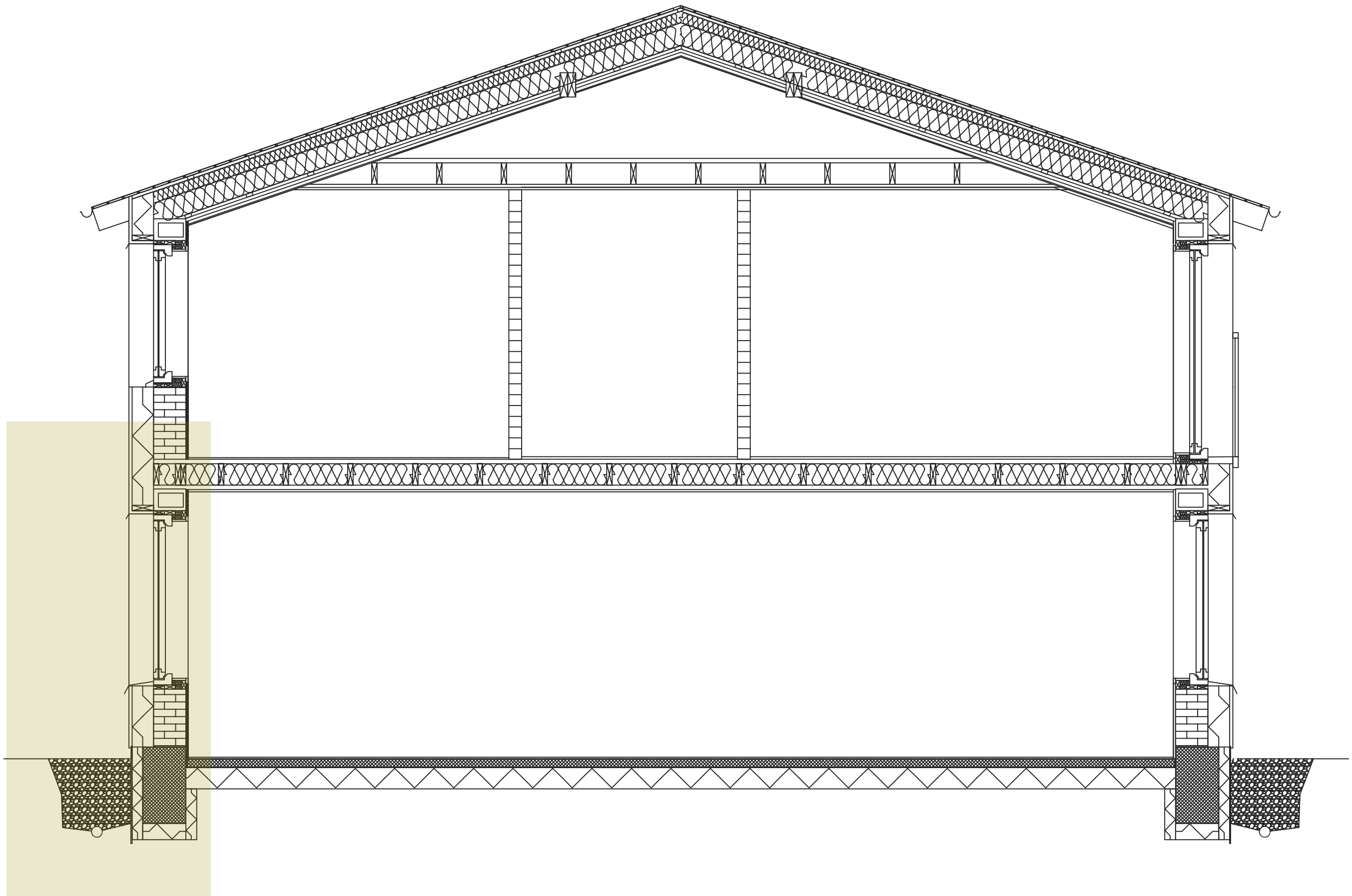


Illustration 44. Section 1:70 (A4).

Redesign

Discussion

Disclaimers

Neither of the four suggestions have had made structural calculations on them. As the walls constructions are based on the walls in the reference projects and the case studies it is assumed that the suggestions are structurally viable, although loads from, for example, snow and wind are different in Höganäs than in the location of the reference projects.

There have been done calculations on the estimated embedded energy of the four suggestions. These were done to see how big the potential for impact could be by using earth as a building material in the walls instead of brick and concrete in the existing rowhouse in Höganäs. The results from the calculations of the suggestions are clear that there is a significantly lower embedded energy in the walls made of earth than in the original. According to the calculations, all four suggestions will save more than 90% of the embedded energy, compared to the original.

However, the results of the calculations are based on numbers that are assumptions and numbers that are missing. Firstly, the embedded energy of the original wall is based on an assumption of what the wall is made of. This was done by using what is known about the wall, that it has load bearing concrete, a brick façade, and is 400 mm thick, and using an existing wall construction using the same materials as the base for assuming the original wall construction in Höganäs. Although the embedded energy of the original wall cannot be entirely correctly calculated, the actual embedded energy is not expected to deviate significantly from the estimated embedded energy.

Secondly, the calculations of the embedded energy of the suggestions are calculated using embedded energy from the raw material in itself (using the numbers from "Embedded energy" on page 15), which will be less than the embedded energy of a finished earth product, for example a CEB. This means that the calculations will suggest a lower embedded energy than what is the case. The actual embedded energy will depend on how the different materials are produced into a product. For example, if the rammed earth was rammed by hand, prefabricated, or using machinery on site will have an impact on the embedded energy, although it is difficult to estimate exactly. Therefore, the contrast between the embedded energy calculations of the original wall, which consist mostly of already processed materials, and the embedded energy calculations of the four suggestions, which consist mostly of raw materials, is probably further increased in these calculations. The calculations of the embedded energy of the suggestions can therefore be seen as an indicator that the suggestions would have a significantly lower embedded energy than the original, although the results are likely to be exaggerated. See Appendix 1 for calculations.

According to the calculations of the embedded energy for the suggestions, it is seen that Suggsetion 2 has the lowest embedded energy (3,1 kWh/m2), closely followed by Suggestion 1 (3,8 kWh/m2), even though Suggestion 1 was meant to be the one with the lowest result. The results are, again, affected by the numbers of embedded energy of raw materials, and the slightly unexpected result here, is probably caused by the thicker walls in Suggestion 1. Suggestion 3 and Suggestion 4 have a significantly higher calculated embedded energy, respectively 20,8 kWh/m2 and 30,2 kWh/m2, which can be seen in the calculation to be largely caused by the lime plaster on the façade. The embedded energy of lime can however be seen as a more realistic number, as lime is a material that does not require significant processing before being able to be built with.

Discussion

Different qualities and priorities set the starting point for the four suggestions now presented. These were: low embedded energy, availability, low erosion, and lastly, an attempt to combine the three aforementioned.

In the first suggestion, a low embedded energy was imagined as a priority for a person building an earth house. The rammed earth will send a strong signal of sustainability by being the façade material. In such a tough climate as Höganäs is with strong winds and precipitation, having an exposed earth façade will probably not be acceptable for many inhabitants of the Swedish west coast. On the inside, the clay plaster will regulate the relative humidity while resembling the clean surface many are used to. The 600 mm thick walls could also be difficult to justify in such a small-scale project as a rowhouse is. Building a house in Sweden using these techniques, however, will probably raise challenges in getting it approved according to the building regulations, and finding qualified craftmanship.

In the second suggestion, all surfaces resemble surfaces that are found in a regular house, a lime plaster façade and clay plaster on the inside. If a different expression is wanted on the inside, the clay plaster could be left out or left out in some places to reveal the CEBs underneath. By having a wooden structure, a common practice in Sweden, the structural calculations would easily be approved according to the building regulations, although by using wood, the embedded energy will be higher than with earth. The wooden façade will not raise any challenges either. The main challenge will probably be to find CEBs to buy, since both laying them, and applying the clay plaster are similar to other more known building materials.

In the third suggestion, a lime plaster is used as the outer façade material to handle the challenges related to earth and water, where low erosion was a priority. By having rammed earth as the inside, the walls will have a unique and strong expression. If a cleaner expression is desired, a clay plaster could be laid atop the rammed earth. Again, building the rammed earth could become a challenge and is probably dependent on the engagement or the building or knowing someone qualified to build it.

The fourth suggestion uses a combination of solutions from the three first suggestion to satisfy as many priorities as possible. The lime plaster façade finish protects the earth from erosion. CEBs as load bearing structure, although it could be problematic in regard to the building regulations, holds the low embedded energy of earth, while being an available building technique. The clay plaster on the inside keeps a clean expression and could be removed to expose the CEBs.

All the suggestions are based on techniques and solutions seen in built projects in Europe. In Sweden, however, the reality of what solutions are available are probably more dependent on the engagement and time of the person building the house, or having luck with finding or knowing someone who knows how to build with earth. In this thesis, there have been made implications on what techniques and solutions are more available than others, but the reality could be different, and again, dependent on engagements or coincidences with available and qualified craftsmanship. How to build with earth is not mentioned in the Swedish building regulations which could complicate the process of building or maybe even exclude some earth building techniques.

Conclusion

Conclusion

How to use the advantages of earth in a building design located in a cold climate?

Global warming is one of the greatest challenges that the world is facing today. The building industry is responsible for around 39% of all emissions and 36% of the world's energy use, which means that changes could have a significant effect. Earth as a building material has a relatively low embedded energy compared to many building materials. The material can be found almost all over and is therefore widely available.

Earth has the ability to regulate the relative humidity levels of its surroundings. In a house with earthen walls, the relative humidity level will stay stable at around 50%, which is considered to be within the optimal range of humidity level. This is an advantage that other materials cannot offer to the same extent as earth. This in combination with the low embedded energy, worldwide availability, and the recyclability of the material, makes earth a sustainable alternative to conventional building materials in a cold climate, for example in Höganäs in Sweden.

Although earth has many advantages, there are also challenges when using earth as a building material, especially in a cold climate like on the west coast of Sweden. Here, extra insulation for the cold, extra protection on the building envelope from moisture, and extra protection from erosion from wind and precipitation in necessary. From all the categories, criteria were set to be able to evaluate earth buildings to what degree they use the advantages and solve the challenges.

In order to find the measures necessary to build with earth in Höganäs, nine earth buildings and their climate in temperate and cold climates in Europe were used as reference projects. These were studied and compared against each other and their climate against the climate in Höganäs. Here tendencies and trends were found, to understand how theory is different from practice on how earth buildings are built.

Three of the reference projects were used as case studies to further examine and evaluate the measures and techniques, and how they are taking advantage of the earth and protecting it from moisture and the weather. Haus Rauch, Haus J, and RoSana Guest House were studied and evaluated using the criteria from the theory chapter. Here it was found that there are several methods and approaches to building with earth and that "the best way" to build with earth depends on what are the priorities and goals.

A rowhouse made of concrete with a brick façade located on the west coast of Sweden, in Höganäs, was chosen to redesign. The purpose of this was to see how the rowhouse could have been built, had it been built with earth. Here four different approaches and priorities set the base for four suggestions for a redesign: Suggestion 1 (low embedded energy), suggestion 2 (easy and available), suggestion 3 (low erosion), and suggestion 4 (a combination). The construction, advantages, disadvantages, estimated U-value, and estimated embedded energy of the different outer walls are described and discussed.

Earth buildings can be built in the cold climate of Höganäs, although the location presents tough conditions. Adjusting techniques and measures from other earth building to the climate of Höganäs makes relevant suggestions for solutions. Depending on the priorities when building, different solutions will be the most relevant one.

To conclude, it can be said that the advantages of earth can be used in an earth building in a cold climate. The low embedded energy, recyclability, and relative humidity regulation are advantages of building with earth, and to achieve the full potential of these, raw untreated earth is necessary. Working with raw earth makes it harder to control erosion and moisture, however, not impossible. To build with earth in a cold climate, knowledge of the material is important. All of the four suggestions of the redesign of the rowhouse, present relevant solutions, representing different priorities when building with earth in a cold climate.

Reflection

There has been an increase in earth buildings in Europe in the last years. Some have called in a renaissance for earth, although the movement is so small that there is hardly a renaissance to speak of in the bigger picture. However, one can say that there has been a shift in the demand for materials that can help lower the high emissions from the building industry.

Materials like concrete and steel will likely be phased out more and more, to rather use materials that are more sustainable and have a lower embedded energy, in order to reach the global emission cuts set by international agreements. Wood is often set as an example of a sustainable material, which it is, compared to concrete and steel. However, wood is not a limitless resource, and cannot easily replace the volume of concrete and steel that is consumed every day in the building industry. There is a need for other materials or new use of existing materials to meet the need for building materials. One of these materials can be earth.

Earth is a material that is widely available all over the world, as stated before. However, it is rarely seen used in cold climates in the developed world. Experiments, research, and studies are necessary to gain knowledge about the material in order for earth to be a viable alternative to other more conventional building materials. Earth can be treated, used in different techniques, and used in different solutions to make it competitive with other more common building materials, but there is a long way to go. Available craftsmanship, knowledge, building costs, and building regulations are examples of factors that are preventing earth to become a popular building material.

In a country like Sweden, where the cost of human labour is high, building with a labour-intensive material, as earth has traditionally been, will require significant effectivization, if earth is going to be a building material that can compete with other building materials, and not just be a material for the particularly interested. Clay plaster and compressed earth blocks (CEB) are similar to other plasters and regular bricks and can probably be implemented into the catalogue of commonly used building materials, if the materials are available, and prices are somewhat similar to these earth materials' respective counterparts. For rammed earth, and wattle and daub, however, which does not have a similar and commonly used building technique, and are very labour intensive, finding a way to prefabricate is probably necessary for it to be a competitive building material. A small-scale factory which produces prefabricated rammed earth elements have been started up by Martin Rauch. Although, for the time being, the elements produced there are so expensive that it cannot compete with the common ways to build houses in Sweden. However, maybe overtime if the awareness and interest for earth increases, the price for these and similar prefabricated elements will decrease enough to compete with other building materials.

This thesis was written as a reaction to a trend in the building industry, where buildings are claimed to become net zero emissions after a number of years, for example, 60 years, using solar panels to generate more electricity than what is consumed. However, in many climate agreements, for example, the Paris Agreement, significant cuts in emissions are required by 2030, in eight years. It is therefore, more important to look at what can be done now to lower emissions. Using materials with a low embedded energy, like earth, will lower the emissions now. This thesis can be seen as a set of suggestions and guidelines on how earth can be used when building in a cold climate, as an effort to spread the word and increase the knowledge on how to build with earth in a cold climate.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Glossary

Rammed earth:
Earth is compressed layer by layer, either by hand or machinery, to form structures

CEB:
Compressed earth block. Earth is pressed into a form with the shape of a brick.

Wattle and daub:
A technique where earth and straw are mixed together and applied like a plaster.

Appendix

Appendix 1

Suggestions	Outer walls		Embedded energy	Total embedded energy	Embedded energy /m2	Savings	Wall size	Material	Embedded energy
Unit	(m)		(kWh)	(kWh)	(kWh/m2)	(%)	(m2)		(kWh/m3)
1 (sustainable)	0,04	clay plaster	104,58	1333,4	3,8	98,9	348,6	Wood	20,25
590 mm	0,2	straw bale	313,74					Insulation	1100
	0,35	rammed earth	915,075					Concrete	700
								Earth	7,5
2 (available)	0,02	clay plaster	52,29	1094,4	3,1	99,1		Lime	900
410 mm	0,11	CEB	287,595					Brick	1140
	0,2	straw bale	288,6408					Straw	4,5
	0,2	wood structure	112,9464						
	0,05	wood cladding	352,9575						
3 (low erosion)	0,25	rammed earth	653,625	7242,2	20,8	93,9			
470 mm	0,2	straw bale	313,74						
	0,02	lime plaster	6274,8						
4 (combination)	0,01	clay plaster	26,145	10536,4	30,2	91,2			
550 mm	0,3	CEB	784,35						
	0,2	straw bale	313,74						
	0,03	lime plaster	9412,2						
Original	0,15	concrete	36603	119093,1	341,6	-			
400 mm	0,2	wood structure	112,9464						
	0,2	glava	70556,64						
	0,02	wood structure	11,29464						
	0,03	brick cladding	11922,12						