FROM THE GROUND UP

Research on Rammed Earth and Timber for a Residential Building

Tobias Helmersson

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Abstract

Rammed earth is a building material that consists of compacted clay, sand, gravel and stones. It is a great option to consider for sustainable constructions, in combination with timber, since earth is abundant almost everywhere and the technique requires minimal energy. However, it is not used as a building material in Sweden today.

This master thesis aims to spread knowledge of the material properties, architectural qualities, and practical applications for rammed earth and timber, show how rammed earth is being used in central Europe today, investigate how rammed earth and timber can be combined to construct a 4-story residential building and explore how the erosion of a weather-exposed rammed earth facade can be an integrated part of the design.

The research method starts with examining the literature on rammed earth and timber. Erosion and pigmentation of rammed earth are then explored further with material tests. Observations from visits to rammed earth projects in central Europe and the company Erden's prefabrication factory are then presented. The knowledge gained from these investigations is then implemented in the design of a 4 -storey residential building of rammed earth and timber.

Timber is a lightweight material that can be used structurally in compression and tension, while rammed earth is heavy and can only be used in compression. These properties, among others, make timber and rammed earth a good combination, which is emphasised in the design.

The design implementation shows that a residential building constructed with rammed earth will need a larger footprint than one constructed with timber only, due to the thicker walls. However, rammed earth offers great qualities such as unique appearance, deep window niches, acoustical and fire separation, recyclability, indoor moisture control and great air quality. But further developments in this technique need to be done for it to become an economically viable option in Sweden. By spreading the knowledge gained from this master thesis to the field, interest might eventually lead to investments in rammed earth construction.

Keywords: rammed earth, timber, erosion, prefabrication, residential.

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My parents
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My background

In 2016 I started the Architecture and Engineering bachelor's program at Chalmers. During those three years I participated in many student union events, was part of the reception committee (AØK) for the new architecture students and organised the bridge building competition (CSDC). At Chalmers I also got the chance to go on several study trips together with the class to explore architecture in different countries.

Architecturally I was first interested in parametric design and bold geometric architecture. These interests led me to my one-year internship in structural engineering at Buro Happold in London, where I developed further skills in parametric modelling in programs such as Grasshopper for Rhino 3D. During that year I started to reflect a lot on the environmental impact of those big Zaha Hadid-like projects in steel and concrete that I was mostly working on.

Although I am still interested in parametric design, my focus has shifted heavily towards sustainability. Within this field I am interested in natural materials such as wood, stone, clay and earth. I find these materials very beautiful, and they have a wide range of beneficial properties besides being sustainable. At EPFL in Switzerland, where I went for a study exchange, I enrolled in a studio that focused on stone architecture, in which we were also introduced to rammed earth. I got excited to explore this great material more so I decided to dedicate my master thesis to it.

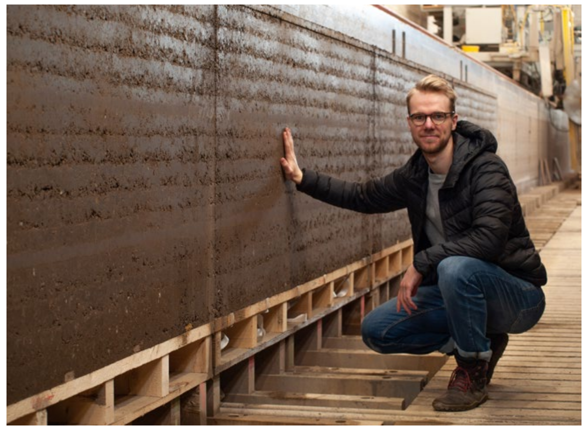

Figure 1. Me in front of the fresh rammed earth wall in the Erden Werkhalle.

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Objectives

The focus of this master thesis comes down to the two materials rammed earth and timber, with their unique material properties. However, since my previous knowledge and that in the construction field is greater about timber, I have deliberately emphasised the research on rammed earth more than on timber.

The main objective of this work is to understand the building materials rammed earth and timber - their material properties, architectural qualities and practical applications, on a deep level. And to show how rammed earth is being used in central Europe today.

With a deeper understanding of these materials, I want to answer two questions: how can rammed earth and timber be combined to construct a 4-storey residential building in Sweden? And how can the erosion of weather-exposed rammed earth facades be an integrated part of the design?

Method

It was clear to me from the beginning that I wanted to show rammed earth used as a building material in a design project. I believe that it is easier to discuss and communicate the benefits of the material with a design in focus. However, since my knowledge of rammed earth prior to the master thesis was very limited, I dedicated a large part of the project to acquire a deep understanding of the material itself. The learning process consisted of three parts: reading, working practically with earth and studying existing rammed earth constructions. Finally, I implemented this knowledge about rammed earth in a design for a 4-storey residential building.

01 Literature review

Early in the process I discovered that there are two different standpoints of what the earth mixture for rammed earth should consist of: 100 % earth without any additives, or earth with the addition of stabilising cement. The addition of cement changes the properties of rammed earth fundamentally, for better and for worse. Most importantly, it defeats the purpose of using earth as a sustainable material. Therefore, I decided to disregard all books that only cover rammed earth with added cement in the literature review. Many of the books that I did read are in some way connected to the Austrian company Erden (also called Lehm Ton Erde) and its founder Martin Rauch. They are the worldwide leading company when it comes to prefabricated rammed earth without added cement. The two architects Roger Boltshauser and Anna Heringer have also written interesting books about rammed earth without cement that I have read. In the literature review chapter, I am presenting a summary of the most important aspects concerning rammed earth, as well as relevant information about timber as a building material.

02 Material exploration

Theoretical knowledge is not sufficient to fully understand a building material. Since earth is locally available for free almost everywhere, it is easy to make rammed earth tests. I conducted all my practical rammed earth tests in Brokind, south of Linköping in Sweden, where my parents live. There I had access to tools and workspace, which I didn't have in Gothenburg. This means that I have only tested earth coming from Brokind, and not Gothenburg, for rammed earth. Besides learning how to work with the earth practically, a big focus was to explore how the erosion of weather-exposed rammed earth can be an integrated part of the design. I also made some different tests with pigmented rammed earth. Most of the rammed earth tests were done during the Matter Space Structure preparation studio.

03 Earth excursion

To deepen my understanding of rammed earth I went on an excursion to Germany, Switzerland and Austria, where I visited 10 recent rammed earth constructions. During the trip I was able to study rammed earth up close and look at a wide range of different details in the constructions. In the earth excursion chapter, I am presenting these observations together with photos. In Austria, I also got the chance to visit Erden and discuss with several of the employees and the founder, Martin Rauch.

04 Design implementation

To show how rammed earth could be used as a building material in Sweden, I implemented my gained knowledge into a design project on a site in Gothenburg. For this I used an existing residential project, the ETC buildings in Västerås by Kaminsky, as a starting point. These buildings are entirely constructed in timber, and I picked this specific project because a similar building typology (height and floor plan) can also be achieved with rammed earth. I changed the vertical structure to be made of rammed earth, while the horizontal structure (floor slab) is still of timber. However, alterations to the floor plan and dimensions of the walls were made to suit rammed earth construction. By using the ETC buildings as a starting point I got a good understanding of how a residential building constructed of rammed earth compares to one of timber. For example, how much the size of the building increases when the floor plan is adjusted to incorporate the thick load-bearing rammed earth walls. I also made other alterations to the design to highlight certain material properties of rammed earth, or to test specific ideas.

The ETC buildings are 4 storeys tall. I kept this height for the design implementation. By using rammed earth for a building that is more than 1-2 storeys I challenge the common notion that structural earth buildings can only be small mud huts. A modern rammed earth building could potentially be even taller than 4 storeys, but the focus of this project is not to push the structural abilities of rammed earth to the limit, but rather to introduce the material in a Swedish context as a viable option for common buildings. With this height for the building, it is also harder to protect the facade from rainfall by a large overhanging roof, which is common for vernacular earth buildings. This means that the erosion of the facades had to be integrated into the design.

The choice to use a residential building for the design is due to that it is the basic building type, necessary even in a severe climate crisis. By focusing on common architecture, I could also emphasize that timber and rammed earth could be used for ordinary projects. Moreover, residential architecture is easy to communicate to most people since we all live in a residential building of some form.

The materials making up the designed building is primarily rammed earth, but also timber. The choice between the two depended on the suitability for the specific location. If none of the two materials were suitable then another material was used in that location, for example in the foundation. The specific design details that derive from the material properties are not hidden, but rather emphasised in the design, to make the understanding of the materials easier.

In the end of the design implementation chapter, the resulting design of the rammed earth building is compared to the ETC buildings.

Figure 2. One of the many erosion experiments on rammed earth I conducted during the material exploration.

Figure 3. During the excursion to central Europe I visited many interesting rammed earth projects, such as this dome structure at ETH, Zürich.

Figure 4. The ETC buildings in Västerås have been used as a starting point for the design implementation.

Delimitations

The cost for constructing the designed building has not been calculated, but consideration has been given to the dimensions of the structure and spaces so that it could be economically viable.

The technical installations in the building, such as ventilation and heating, have not been described in detail. However, enough space for such installations has been added in the design.

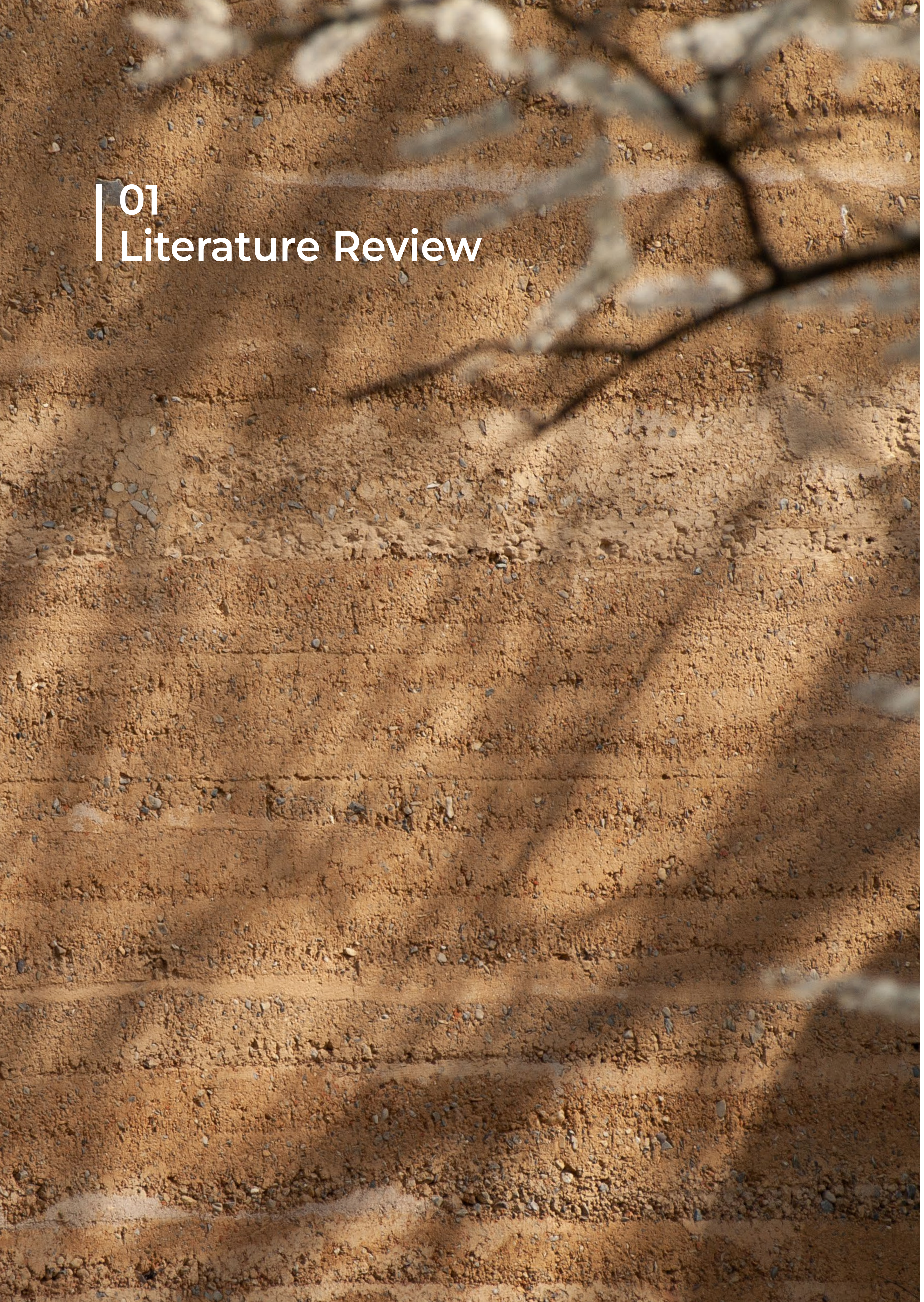
The exact composition of the earth in Gothenburg has not been examined. Differences might exist between the earth I used for the material testing and the earth in Gothenburg.

There are many earth and clay building techniques available, but only rammed earth and clay plastering have been described and used in the design.

The structure has not been dimensioned according to thorough calculations, but only through estimations based on reference projects and literature.

Both rammed earth and timber have the potential to be more sustainable options and emit less greenhouse gas than concrete and steel. But a calculation and comparison of the emissions is not included in this project.

The detail plan (detaljplan) of the site has not been followed strictly.



01 Literature Review

What is earth?

Earth can be seen as a mineral skin covering our planet, in chemical equilibrium with the atmosphere. Its different components that we call clay, silt, sand, gravel and stone are all just different particle sizes of weathered and decomposed rock (Boltshauser et al., 2018, p. 168).

Similar to how cement is the binding agent for concrete, clay is the binding agent for earth (Boltshauser et al., 2018, p. 168-170). The small clay particles are shaped like plates, often smaller than 2 µm, which gives them the important cohesive properties when combined with water. The water forms capillary bridges between the clay particles, which is the same kind of forces keeping a sandcastle together or two glass panes with water in between.

Earth with about 20 - 30 % clay can be compacted in layers and be used as a building material, which is called rammed earth. The earth mixture for rammed earth could contain stones up to 3.2 cm in diameter (Heringer et al., 2019, p. 52). No organic matter is wanted in the mixture, but about 10 - 15 % water content is necessary.

As long as these base conditions are met, different earths can be used for rammed earth construction (Boltshauser et al., 2018, p. 102). There is not an exact formula for the earth mixture. This means that earth suitable for rammed earth can be found locally across the globe. It can have different colours depending on various minerals and different properties for construction. To ensure the properties of a specific earth sample, a rammed earth test should be made and examined.

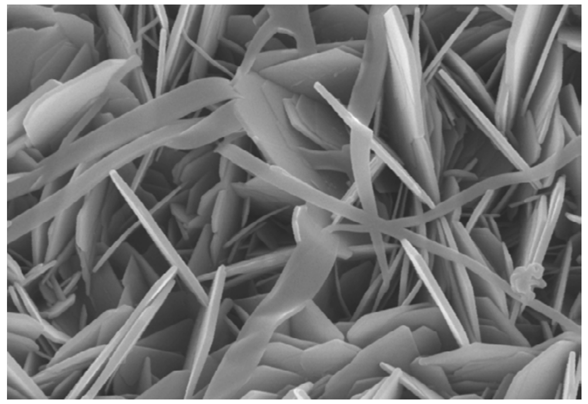


Figure 6. Clay particles are often formed as thin plates smaller than 2 µm, this gives clay its important cohesive property.

Figure 5 (left). Rammed earth wall of the Etosha House in Basel Zoo.

Rammed earth

History
Rammed earth is not a new material or building technique. In fact, earth could be the first ever building material used by humans (Maachi et al., 2020). Through history it has been used on all continents in a wide variety of constructions. Many of which are still standing today, such as parts of the Chinese wall, Al Hambra and many residential houses in the Lyon/Geneva region. It is estimated that 30 % of the world's population even today live in earthen constructions. There is also a tradition of building with earth in Sweden, the rammed earth technique is called "stamphus" here (Palmgren, 2003).

Although, it is not common to see new buildings constructed with earth in industrialised countries today. The new materials from the industrial revolution took over completely and earthen building techniques were forgotten (Boltshauser et al., 2018, p. 6). A big reason for this was that earth was hard to standardise and therefore hard to capitalise on in the same way as for example concrete and brick.

Revival
Now a revival of earthen building techniques has started to happen. The company Erden in Austria has developed a technique for prefabricating rammed earth wall elements that can be stacked to construct large scale buildings. This technique has already been used successfully in a variety of projects such as the Ricola Herb Centre, Alnatura Campus and the Swiss Ornithological Centre. The projects of this company are located mainly in Austria, Switzerland and Germany, and all of them are constructed with unfired earth without stabilising additives (Erden, 2022a).

Figure 7. Old rammed earth barn in France, approx. 150 years old.

Material sourcing
Ideally, the earth used for construction could be taken directly from the excavated earth of the building site, which would lead to less emissions from transports. This was done for Haus Rauch in Austria, where 85 % of the material for the entire house was taken directly from the excavation pit (Boltshauser et al., 2018, p. 178). Sometimes the earth on the building site is not suitable, in that case there is an opportunity to take advantage of the large amounts of excavated earth from other construction sites and infrastructure projects. Earth actually represents the largest amount of waste material in industrialised societies (Boltshauser et al., 2018, p. 164). For example, over two million tons of excavated earth are transported out from Paris and deposited in landfills every year (Heringer et al., 2019, p. 105). 90 % of this is estimated to be usable for earthen constructions. Excavated earth from large infrastructure projects in Gothenburg, such as Västlänken, could potentially be used for construction as well.

The ramming process
The earth is poured in 12 - 16 cm thick layers in a formwork, like the ones used for concrete, and then compacted with hand tools or mechanical tools to half its thickness (Heringer et al., 2019, p. 52). The process is then repeated to successively build up the wall layer by layer. No firing is needed, the wall will gain strength by drying. The wall can be built in its entirety in situ or by prefabricating wall elements in a factory.

Figure 8. The Chapel of Reconciliation in Berlin, 1999-2000, is the first load-bearing rammed earth structure built in Germany for 100 years (Erden, 2000)

Prefabrication

The company Erden in Austria has developed this prefabrication technique, and they are currently the only company that does it so far (Erden, 2022a). Prefabrication is advantageous compared to in situ since it is not depending on the weather or construction site schedules (Heringer et al., 2019, p. 51). In their Erden Werkhalle they normally ram 50 - 80 m long and 1.3 m tall walls automatically by machine. This long wall is then split into separate elements, before drying for 4 - 6 weeks in room temperature to reach its full compressive strength, which is 10 times bigger compared to the fresh damp rammed earth (Boltshauser et al., 2018, p. 170). When drying it will also shrink somewhat, but it is beneficial that this shrinkage and increase in load-bearing capacity happens before the assembly of the elements. For in situ construction the wall cannot be constructed too fast since the lower part of a tall wall then will not be able to withstand the loads, and since the shrinkage due to drying in a large wall might result in cracks.

It is possible to integrate a layer of insulation in the prefabricated elements (Erden, 2022b). Erden has produced such cavity walls for one project, Alnatura Campus in Darmstadt, where they integrated foam glass insulation directly in the ramming process.

The rammed earth elements typically weigh 4 - 7.5 tons (Erden, 2021). The crane used for the construction, as well as the transportation of the elements, must be taken into consideration when designing the size of the wall elements. For large scale projects Erden have set up prefabrication factories in proximity to the building site to reduce transportation costs and emissions.

It is worth noting that constructing rammed earth in situ might be better in contexts where the cost of labour is cheap and industries are sparse.

Figure 9. Foam glass insulation integrated in the ramming process.

Figure 10. Slicing of the long rammed earth wall into smaller elements.

Figure 11. Prefabricated wall elements drying for 4 - 6 weeks.

The prefabricated elements are stacked together with a crane on the construction site and fixed together with earth mortar (Erden, 2022a). To ensure a continuous appearance of the inherent horizontal lines produced by the ramming process the elements should be placed in the same order as they were cut in the factory. And as a final step they are retouched by hand to create a monolithic appearance similar to that of in situ construction.

The elements should be stacked in a masonry bond and not directly on top of each other (Erden, 2021). In that way point-loads are distributed, and the lateral stability is increased. A wall with corners or shear walls will also be inherently more stable to lateral loads. A ring beam or other detail that connects the elements will further increase the stability.

Figure 12. Lifting the elements on place with a crane.

Figure 13. Retouching the joints to create a seamless monolithic appearance.

Figure 14. The finished result of the Ricola Herb Centre, made from prefabricated elements.

Load-bearing

Rammed earth structures can withstand compressive forces of about 2.4 - 3.5 N/mm² (Erden, 2022a), this can be compared to 12.5 N/mm² for normal concrete (Heringer et al., 2019, p. 118). However, the lower strength of rammed earth compared to concrete is not an issue as long as this is taken into consideration in the design. The tensile strength of rammed earth is about 10 % of its compressive strength (Minke, 2006, p. 33), which means that it can handle limited lateral load. To withstand intense earthquake loads, it needs to be combined with other materials. It should not be used for structural tension elements such as beams or floor slabs. With a correct understanding of these properties, rammed earth can be used as a structural load-bearing material. The structures tend to be massive, with thicker walls at the base in some cases.

Other materials such as wood, reinforced concrete or steel can be used in combination with rammed earth to span floors and as lintel beams over apertures (Rauch, 2015). The lintel beams can be concealed or exposed. Wide windows are not suitable since the heavy wall above it will require a large lintel beam to span the opening. A way to omit the lintel beam completely is to continue the aperture all the way up to the roof. Arched shapes that are only subjected to compressive forces is another way to create apertures. This can be used not only over small apertures but also for more complex compressive structures like the rammed earth cupola at ETH Zurich (Boltshauser et al., 2018, p. 212). This structure was constructed by prefabricating half-cone elements, which were rotated during assembly and fixed together with clay mortar.

Rammed earth structures are subject to creep deformation over time (Erden, 2021), which means that connections that allow movement should be implemented to avoid cracking. But this behaviour is not unique for rammed earth, so a wide variety of solutions have already been developed.

Height

How tall a rammed earth building could be is yet to be discovered. But Haus Rauch is a 3-story building constructed with 45 cm thick load-bearing rammed earth walls (Boltshauser et al., 2011). Historically there are many earthen constructions taller than that. For example, the city of Shibam in Yemen which was founded in the 16th century has many earthen buildings of 5 - 7 stories tall (Dethier, 2020). The walls for these buildings can be up to 1 m thick at the base and taper to 30 cm at the top. And the tallest earthen structure in the world is believed to be the 53 m tall minaret of the Al-Mihdhar Mosque in Tarim, Yemen, built in 1914. Another example is the 6-story tall Haus Rath in Germany, built around 1850 and still in use today (Escobar, 2013).

Figure 15. The ETH Cupola is a compression-only structure.

Figure 16. Numerous earth buildings of 5-7 stories are located in the city of Shibam in Yemen.

Embodied energy

Compared to other building materials rammed earth requires minimal energy during construction. The earth does not need to be fired like bricks or cement. After the damp mixture has been rammed, the formwork can be removed and the wall will dry at room temperature. The tools and transportation are the only things requiring energy during the construction. A study of the rammed earth facade on Ricola Herb Centre concluded an 87 % reduction in embodied energy compared to average values of a conventional lightweight facade (Heringer et al., 2019, p. 106).

Recyclability

Time does not alter any properties or chemical composition of the material (Heringer et al., 2019, p. 107). So, if no additives have been added to the mixture, the material can simply be transformed back to its original form by crushing it and adding water. This means that the material can be recycled endlessly without degradation, or just left on site to become a part of the nature again. It is also simple to separate embedded installations and construction parts from earth which makes full recyclability easier.

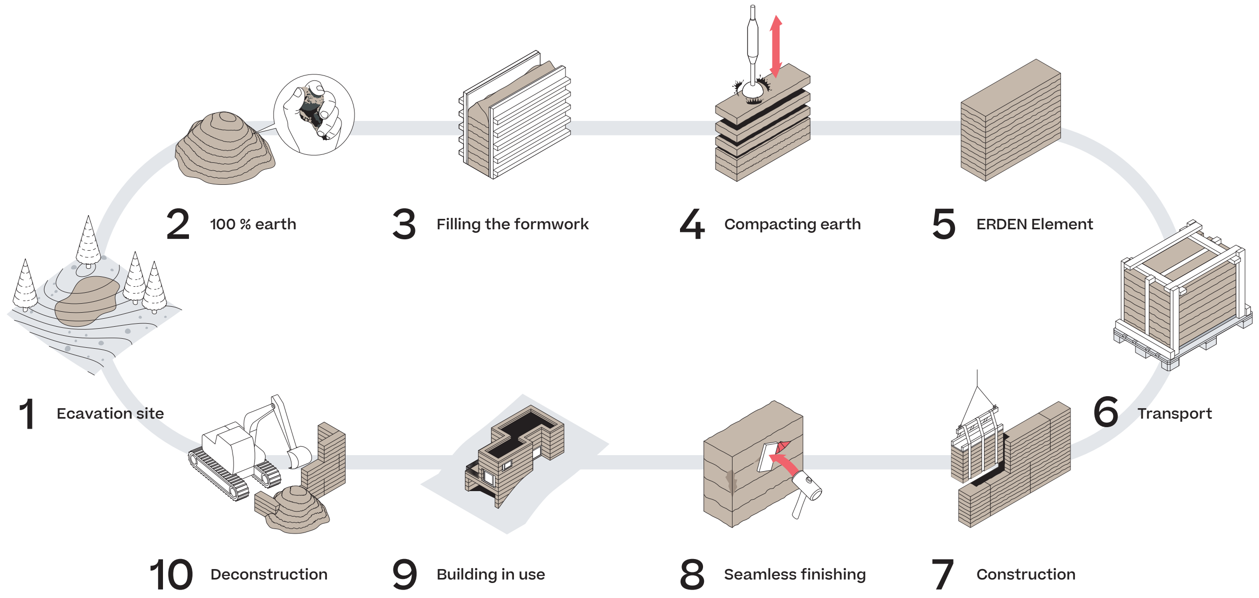


Figure 17. Earth is a circular material that can be reused endlessly.

Calculated erosion

Earth is water-soluble which indeed makes it vulnerable to weathering and erosion (Heringer et al., 2019, p. 48). This is why historically earthen buildings normally have been protected by a large overhanging roof (Heringer et al., 2019, p. 117). Splashing and rising water also affect the wall, so it should be placed on a water-resistant plinth (Rauch, 2015, p. 65).

Although, in modern architecture, big overhanging roofs are not often desired anymore. But this challenge can also be met with other design features according to the principles of calculated erosion. In this case the initial wall should be built 2 - 3 cm thicker than otherwise planned (Heringer et al., 2019, p. 48). As water flow on the facade the outermost layer of finer particle sizes will wash away first (Rauch, 2015). The bigger stones and gravel then get exposed and self-stabilise the surface of the wall. When the clay particles between the stones get wet they will expand and hinder the water from penetrating deeper, which will reduce the pace of erosion.

Horizontal lines of erosion checks can also be implemented to protect the facade further. They will reduce the speed of the water flowing on the facade and thereby reduce the erosion. These can be protruding ceramic tiles, as on Haus Rauch, but other materials such as stone, lime plaster or metal could also be used. Many projects globally rely on these principles of calculated erosion, and they have proven that after the initial centimetres of erosion the facade ceases to recede (Heringer et al., 2019, p. 49).

The surface can be plastered at any stage of erosion, if the rough appearance is unwanted. However, this is not necessary. Just like the greying of timber the erosion can instead be seen as something beautiful.

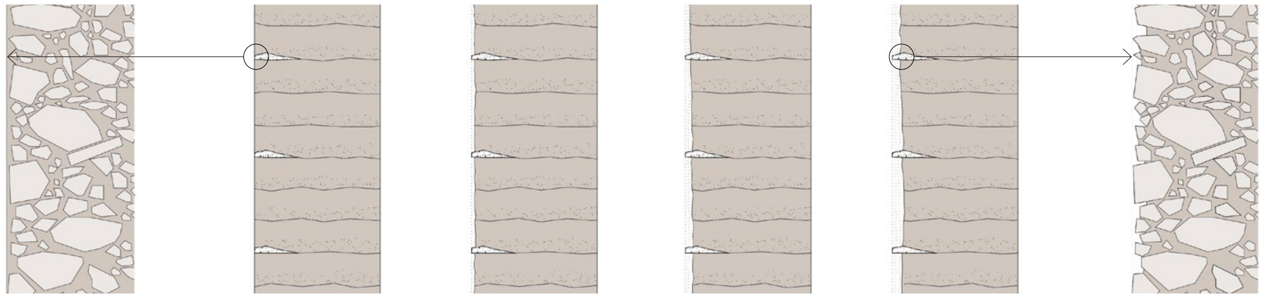


Figure 18. The rammed earth wall will erode between the erosion checks and get a rougher surface.

Figure 19. The smaller particles will wash away and reveal the stones, like this facade on Haus Rauch.

Stabilisation

Instead of working with the raw earth as it is, some people are altering it by adding stabilisers of cement or lime to increase the strength and make it water-resistant. This is often the case in the USA and Australia (Heringer et al., 2019, p. 48), and most of the images from a google search are showing stabilised rammed earth with cement. In these cases, it is common to add between 5 - 10 % cement, this can be compared to 12 % cement which is common in concrete. But since the rammed earth structures are massive, the relatively small amount of added cement will result in high embodied carbon. Moreover, the addition of cement will impede two of the most valuable properties of rammed earth, its full recyclability and its ability to buffer and exchange moisture (Rauch, 2015, p. 65).

Air quality

Dry rammed earth still contains a small amount of free water (Boltshauser et al., 2018, p. 170-174), and as the humidity increases, more water will condensate between the clay particles and be captured by the earth. A clay surface can absorb about seven times more water vapour than a painted plasterboard surface. This ability to exchange moisture with the environment makes earth a great indoor humidity regulator.

An indoor humidity between 30 - 60 % is considered good. (Boltshauser et al., 2018, p. 174). Higher humidity can be uncomfortable and cause damage to structures. Low indoor humidity, on the other hand, can lead to respiratory problems, dry eyes and skin. A room with clay surfaces tends to be stable at around 50 %, which is optimal for human health. To retain these properties, all vapour tight membranes should be avoided in rammed earth walls (Erden, 2021).

Furthermore is a rammed earth wall able to balance out the vapour pressure between inside and outside (Boltshauser et al., 2018, p. 174). It is able to breathe, unlike most new buildings which are completely sealed with vapour barriers to stop the movement of the moisture. This is demanding more ventilation which then leads to bigger heat losses in winter. A study on Haus Rauch showed that this property results in lower energy need for long term operation (Heringer et al., 2019, p. 48).

The small particles in earth also filter the air and bind pollutants (Boltshauser et al., 2018, p. 174). The air in clay and rammed earth houses is often perceived as fresh and free of odours by the people who live in them. Earth's equilibrium moisture content of 6 - 7 % combined with its antiseptic properties also prevents the formation of mould (Boltshauser et al., 2011, p. 150-152). And by not using any plastics, silicones, synthetic adhesives and colour, potential pollution from harmful substances can be completely avoided.

"The envelope that surrounds us should be able to breathe and diffuse in the same way as our bodies. My buildings are therefore deliberately not encapsulated, sealed, or made smooth with synthetic or high-density, energy-intensive materials; rather, they are assembled and finished in raw form, like sushi - left uncooked!"

Martin Rauch
(Boltshauser et al., 2011, p. 74)

Preserves wood

The ability of clay to absorb moisture is ideal in combination with wood and has been successful in practise for millennia. Clay's equilibrium moisture content is 6 - 7 % while timber eventually balances out around 9 % in constructions (Rauch, 2015, p. 108). This means that the clay will dehumidify the timber in the event of excess moisture. Moreover, the clay will create a favourable microclimate and protect the wood against vermin infestations. (Boltshauser et al., 2018, p. 173). However, it is crucial that any gaps between the rammed earth and timber is adequately filled with earth to avoid condensation within the structure, in that way the moisture will be absorbed and transferred within the earth without causing damage to the wood (Rauch, 2015, p. 108).

Thermal capacity
The high thermal mass of earth and the thick walls, enables rammed earth constructions to function as a heat buffer (Erden, 2021). This means that the peaks in daily temperature fluctuation are flattened, which will reduce the energy consumption from indoor climate control. This property has been used extensively in warm climates. The indoor temperature of massive earthen buildings in such climates will be stable close to the average outdoor temperature between night and day. This principle also works great in colder climates, but then insulation is also necessary because the average outdoor temperature in colder regions is too cold for the indoors.

Acoustics
Thanks to rammed earth's high density and large mass it can provide great sound insulation to meet acoustic requirements (Erden, 2021). The rated sound reduction index is 53 dB for a 20 cm thick wall. Due to the many irregularities of a rammed earth surface and the varying hardness, this material will also substantially reduce echoes and reverberation within a room. The acoustic environment in such spaces has been described as both cosy and felted (Grunacker, 2021, p. 54). Although, just like for concrete and brick the high density of the material also means that the transmission of structure-borne sound is high, which means that structural parts may need to be acoustically decoupled (Erden, 2021).

Fire resistance
Earth is a non-combustible material and rammed earth constructions have met the highest fire protection requirements according to the Austrian OIB guidelines. The fire resistance class of a 25 cm thick rammed earth wall is RE90 (Erden, 2021).

Price
Ramming earth on site is very labour intensive and therefore results in high costs in contexts where human labour is expensive (Heringer et al., 2019, p. 108). However, standardisation and prefabrication are showing the potential to reduce the cost significantly. The retail price for Erden's prefabricated rammed earth wall elements is currently 1000 - 1200 €/m², with a production cost of 850 - 1000 €/m². Although with their recent improvements of this technique and an anticipated increase in use, they expect that the retail price soon could be 600 - 800 €/m² and the production cost 500 - 600 €/m².

Another important aspect to consider when discussing the price is what cost is set for carbon emissions, this will likely rise soon in benefit to low emission building materials like rammed earth and wood.

Rammed earth floor
Rammed earth floors cannot span spaces on their own in multi-story buildings, because of the low tensile strength of the material. This is only possible if the floor slab is in vault form, which requires substantial space beneath. However, by using timber as the structural material in the floor slab a rammed earth floor can be added on top.

This type of floor slab was used for Haus Rauch with a 10 cm rammed earth floor on top of load-bearing timber beams spanning in one direction. The surface is polished and waxed to create a nice and durable finish. Erden has developed the technique further and is now able to integrate footfall sound insulation as well as water pipes for floor heating (Rauch, 2015, p. 61).

This type of floor slab has many potential benefits compared to a floor slab of only timber. Earth has, as mentioned earlier, the ability to passively regulate indoor humidity and temperature as well as preserve wood. Besides that, the addition of a heavy material will increase the sound insulation between stories. Since earth is a non-combustible material this method could also be beneficial for fire protection. And in tall lightweight timber buildings, this type of floor slabs could be used to add extra weight for stability, instead of adding concrete.

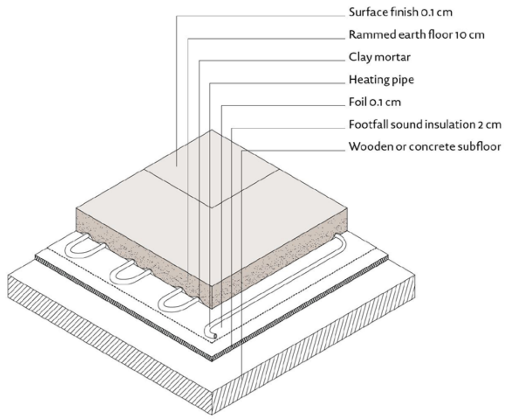


Figure 20. Rammed earth floor construction detail by Erden.

Figure 21. A finished rammed earth floor in Haus Rauch, similar to how a polished concrete floor can look, but with more texture.

Timber

Engineered wood products

Timber has been used extensively as a building material through history. Recent technical developments have further increased the possibilities for wooden constructions and resulted in a wide range of so-called engineered wood products, for example Cross Laminated Timber (CLT), Glulam, and Dowel Laminated Timber (DLT). With sawn timber there is always a risk for internal imperfections which could lead to failure. So, the main idea with these products is to join smaller lamellas together to a bigger piece, and thereby reducing the risk of imperfections effecting the structural ability of the whole piece (Hildebrandt et al., 2017). There are many companies working with prefabrication of CLT elements in Sweden: Stora Enso, Moelven, Derome and Södra among others. The maximum size of Södra's CLT slabs in their new factory is 16 x 3.5 m (Blomster, 2022).

Height

Thanks to the technical advances, timber buildings are also increasing in hight rapidly. Recently, the 20-story tall Sara Kulturhus in Skellefteå was completed (figure 22). It is now the tallest timber building in Sweden. A challenge when building tall with wood, is to ensure structural stability because the building is too lightweight. Extra weight can be added to the building, and thereby increase its stability, by incorporating some floor slabs of concrete. This was done for Sara Kulturhus (SVT, 2021). Rammed earth floors could be another way to achieve more weight, as mentioned earlier.

Figure 22. The wooden highrise Sara Kulturhus in Skellefteå during construction.

Climate impact

The building industry is currently relying on wood in the transition to more sustainable constructions. Wood is composed of carbon sequestered from the atmosphere. By using it in construction this carbon can be stored and the buildings act as a carbon sink (Lundmark, 2020).

The carbon emissions from the production of wood are still lower than that of concrete and steel, even if the carbon storage is omitted from the calculations. A study from Linköping University suggests that the carbon emissions from a building constructed of wood are 40 % lower than a similar building constructed of concrete (Brege et al., 2017).

However, there is a big problem in the forestry industry with the conventional method of clear-cutting large areas of forest (Brunn, 2021). This is not only problematic for the habitats of animals, but it also results in nutrient leakage from the soil and carbon emissions from the degradation of residues. It usually takes up to 20 years for a growing forest to compensate for the carbon emissions of the clear-cut.

Continuity forestry is an alternative to clear-cutting, where only the biggest trees are cut and max 25 % of the trees are cut at the time (Brunn, 2021). The continuous vegetation will then enable wildlife to survive and impede the leakage of nutrients and carbon emissions. The smaller trees will then also be exposed to more sunlight and grow faster to capture more carbon.

Figure 23. The conventional method of clear-cutting results in nutrient leakage and carbon emissions from the open area.

Acoustics

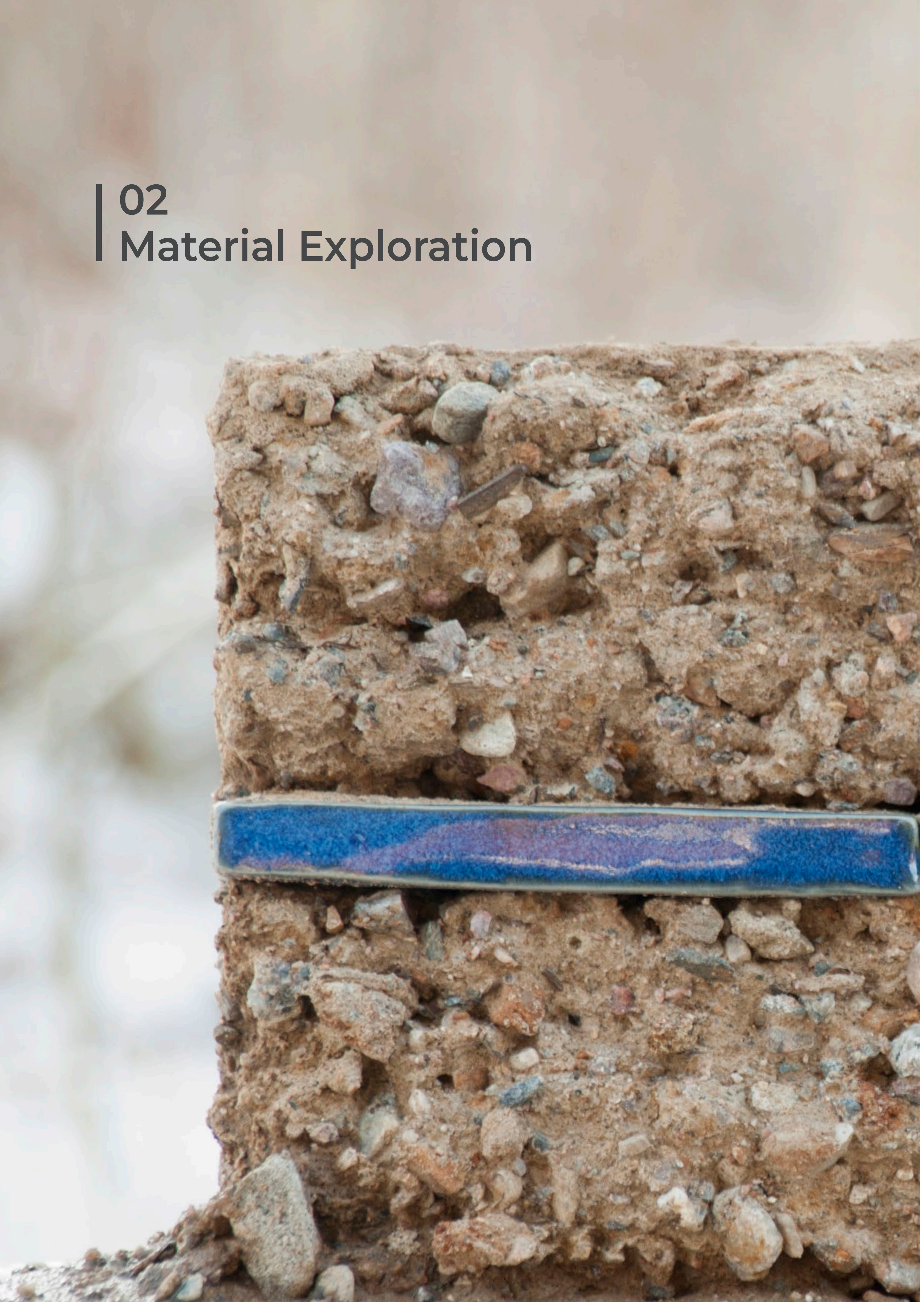
Lightweight materials like wood are not as good sound insulators as heavier materials, like stone, concrete and earth. Different solutions have been developed to meet the acoustic requirements for wooden floor slabs between apartments. A common solution is to make a double layer slab with a gap in between (Gustafsson et al., 2012, p. 10). Or to incorporate another heavier material in the slab, such as concrete or gravel. A consequence of this is that the wooden floor slabs normally constructed are thicker than slabs in concrete or steel.

Moisture

Temporary periods of high humidity with drying in between are not harmful to wood. For example, an exposed wooden facade can handle normal rainfall with dry days in between. Although, rain as well as sun exposure, can cause a shift in colour, which may be desired or undesired. Water becomes a problem for wood only when it is not free to dry out. The damages caused by excess moisture over time can affect the structural integrity and indoor air quality due to mould. Problems like these can occur due to moisture convection if the building is not vapour-tight or if water does not run off properly from a facade and remain on the wood. Common practice to prevent moisture damage in wooden constructions is to install vapour tight membranes (Gustafsson et al., 2012). However, if the membranes are damaged and water or vapour finds its way in, it can get trapped in the structure without the possibility to dry out, and thereby cause damage.

Fire resistance

Wood is a combustible material, but massive timber in constructions can handle fire relatively well despite that fact. The charring of the wood during a fire will decrease the speed at which the fire is burning through the wood (Al-Emrani et al., 2013, p. T21). The charring will reach about 40 mm into the wood after 60 minutes. So, by increasing the dimension of the wood, the structural stability of the construction will be assured for a longer time during a fire, and this is often the cheapest way to protect against fire in timber constructions. Other protective measures like fire protective paint, covering with plasterboards and sprinklers are also commonly used.



02 Material Exploration

To get a better understanding of the earth material, I decided to work and experiment with it practically. This was done during the Matter Space Structure preparation studio during the fall of 2021. I conducted all these experiments in Brokind, south of Linköping, where my parents live, since I had access to tools, space as well as earth there. I could probably have done this in Gothenburg as well, but it was just easier to do it in Brokind. However, I created the ceramic erosion checks in a workshop in Gothenburg.

One of the most common questions people ask when I say it is possible to build with rammed earth is: will it not rain away? It is true that some erosion will occur in the beginning, but from the literature review I have learned that this is not so much a technical issue but rather a psychological one. So, to tackle the psychological issue of building with a "weak" eroding material I decided to focus the material experiments on how the erosion can be an integrated part of the design, which would hopefully lead to a bigger acceptance of the erosion.

I was also curious to explore pigmentation of rammed earth. The result of this exploration is presented in the end of this chapter.

Figure 24 (left). Test with eroded rammed earth and ceramic erosion checks.

Finding suitable earth

Before performing any practical tests, I had to find suitable earth. A clay content of about 20 - 35 % is wanted for rammed earth. A quick test to roughly examine the clay content is to form a small ball of the earth and drop it from 1.5 m. If the ball disintegrates into many pieces, that indicate a low clay content. But if the ball breaks into just a few bigger pieces, the clay content is potentially good. If the ball doesn't break at all and just splashes or becomes flatter, then the test indicates a very high clay content or too much water.

To estimate the clay content better, a sediment test can be made. The earth is then placed in a jar with water. After the jar is sealed, it is then shaken extensively and left untouched for 24 hours. The particles will segregate due to their varying weight, resulting in the bigger stone, gravel and sand particles at the bottom of the jar and the smaller clay particles at the top. If there is any organic matter it will float on the water surface. Then the clay content can simply be measured with a ruler.

I first tried using earth from my parents' garden in Brokind, Sweden. Since the earth should be free from organic matter I had to dig to a depth of about 65 cm (figure 26). Unfortunately this earth had a very low clay content as both the ball drop test (figure 28) and the sedimentation test (figure 29) showed. In a garden nearby I found a big pile of excavated earth next to a newly built house (figure 30). The clay content in this earth, according to the tests, was about 26 %, which is in the optimal range.

I estimated the volume of the excavated earth pile next to the newly built house to be about 80 m^3. This was done by 3D-scanning it with the help of a drone and photogrammetry. Rammed earth is compacted to 50 - 65 % of its original volume, so this pile of earth would be enough for 40 - 50 m^3 of rammed earth construction. A 33 - 42 m long, 3 m tall and 40 cm wide wall could be built from this.

Figure 25. 3D model of the excavated earth pile, obtained from drone photographs and photogrammetry.

Figure 26. I dug a 65 cm deep hole in my parents' garden in the search for suitable earth.

Figure 30. A pile of excavated earth next to a newly constructed house in Brokind.

Figure 27. Ball drop test 1.

Figure 28. The ball disintegrated in many small pieces.

Figure 31. Ball drop test 2.

Figure 32. The ball broke in fewer and bigger pieces.

Figure 29. Sediment test of the earth from my parents' garden.

Figure 33. Sediment test of the excavated earth.

Ceramic erosion checks

In Haus Rauch, unglazed ceramic tiles are used as erosion checks, as seen on page 18 (figure 19). There they are made from clay of the same colour as the earthen wall. To increase the contrast between the rammed earth and the erosion checks I made glazed ceramic tiles in different colours. This will also emphasise that the calculated erosion is an intentional part of the design. I made them in half scale since I was not allowed to burn thicker tiles in the available oven. During the process, some of these became slightly bent, but the intention was to create straight ceramic tiles.


Figure 34. Kneading the clay.


Figure 35. Cutting the clay.


Figure 36. The unfired tiles.


Figure 37. The kiln used.

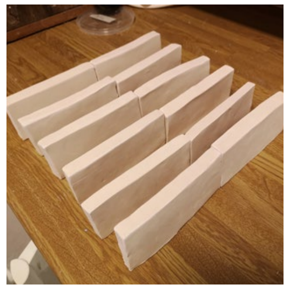


Figure 38. After the first firing.


Figure 39. Dipping the tiles in glazing.


Figure 40. Glazed tiles ready to be fired.


Figure 41. The finished ceramic tiles.


Figure 42. The glazed ceramic tiles with different colours will be used as erosion checks in the rammed earth.

Erosion tests

I created several test blocks of rammed earth to conduct erosion tests on. Their size was 13 x 15 x 23 cm and weighed 10 kg each. These were made by compacting the earth in 4 layers inside a wooden formwork with a pole.

The erosion checks were inserted halfway up in the test blocks, at a depth of 5 - 10 mm from the surface. Normally, the erosion checks are placed flush against the surface of the wall or protruding slightly as in Haus Rauch. In this case, they are hidden from the beginning, but as erosion progresses they are slowly revealed. This means that the appearance of the building will change more drastically over its lifespan, and the erosion process is more emphasised.

After 3 days indoors the blocks had dried and hardened so I could take them outdoors again to perform the erosion tests. The erosion that normally would take decades was simulated with the help of high-pressure water in a few minutes. The wet rammed earth is darker than the dry rammed earth, as can be seen in the photos.

The erosion checks can be seen as ornaments on the facade that grow over time. Some will appear before others, depending on how exposed different areas of the facade are. Exactly how this pattern would look is hard to predict since it depends on the weather, but it could be controlled to some extent with protruding roofs for example.

The photomontage on the next page is showing in detail how the appearance of a rammed earth facade could change as erosion progress (figure 52). It can be seen as a timeline for a facade, showing it as newly built to the left, and after many years of erosion to the right. But the whole image could also show the same moment, in a scenario where the left part is more protected, for example by a balcony or roof. The centre is showing how the erosion checks are just starting to become visible, appearing like treasures in the ground.

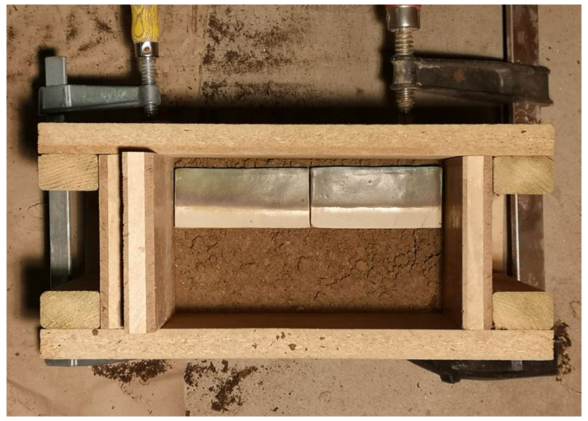


Figure 43. Insertion of ceramic erosion checks.


Figure 44. Rammed earth blocks drying inside.


Figure 45. The ceramic tiles are hidden 5 - 10 mm deep in the rammed earth.


Figure 46. Uneroded and dry rammed earth.


Figure 47. The wet rammed earth is darker than when dry.


Figure 48. The erosion is starting


Figure 49. As the erosion progresses the erosion checks start to appear.


Figure 50. The erosion checks are now fully revealed.


Figure 51. The rammed earth turns brighter again when it has dried.

Figure 52 (next). How the erosion could progress on a facade.

Pigmentation

The appearance of the rammed earth can be modified with pigmentation. Below are samples with red iron oxide, black iron oxide and yellow ochre mixed with the earth in 4 different quantities (figure 53).

The yellow ochre gave a very small difference in appearance compared to the others. This could be because yellow is closer to the colour of earth, compared to red and black. The pigment giving the yellow colour to the ochre is in fact also iron oxide. But I noticed that the iron oxide content in the yellow ochre is only 10-15 % compared to 90 % in the red and black iron oxide, so this could also be a reason for the small difference.

To test the pigmentation in a bigger rammed earth block I mixed in increasing amounts of red iron oxide with 2.5 kg of earth (figure 54). By compacting one layer at a time, I created a gradiented rammed earth block.

It could be interesting to allow for deeper erosion in some parts of the facade. This could be done by directing the water from the roof to certain areas on the facade instead of in pipes. If the facade is pigmented as a function of depth, then the colour would change depending on the depth of the erosion. To test this, I rotated the red gradient rammed earth block and applied high-pressure water to it.

The eroded pigmented rammed earth turned out less red than the uneroded red surface. The reason for this is that the pigment is mixed with the smaller particle sizes, which wash away before the bigger stones. Since the washed stones don't have any pigment left on them, there is less red on the surface. The pigment washed away even with shallow erosion, so pigmented rammed earth is probably more suitable for indoor use, where there is no erosion.

It might be a better idea to use stones in different colours mixed in at different depths to achieve the effect that the rammed earth is shifting in colour as the erosion depth increases. For example, using white/bright stones would be interesting because then the building would turn brighter as it gets eroded and older, as opposed to a concrete facade which often gets dirty and darker over time.

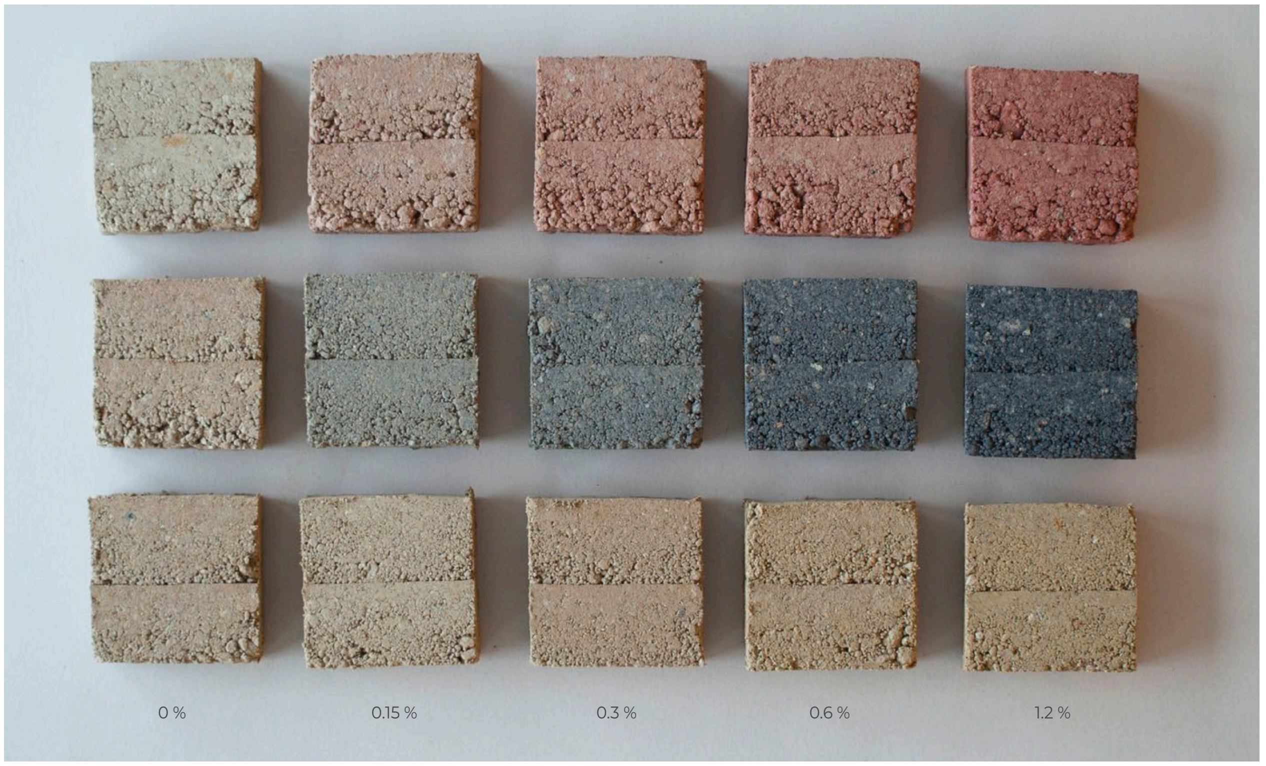


Figure 53. Samples with different quantities of pigmentation.

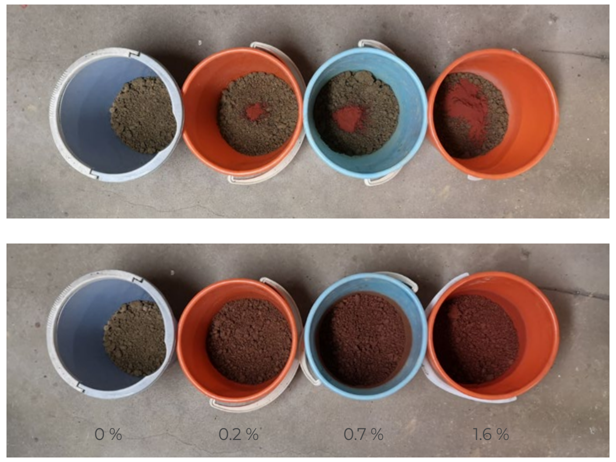


Figure 54. Pigmentation mixed with 2.5 kg of earth for each layer.

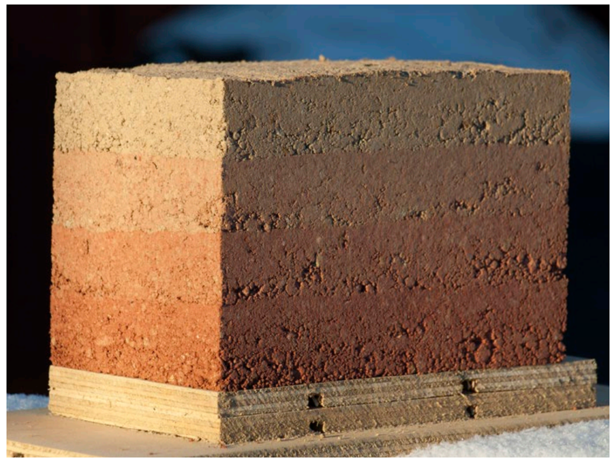


Figure 55. The pigmentation resulted in a nice gradiented rammed earth.

Figure 56. Rotated for testing deep erosion through all layers.

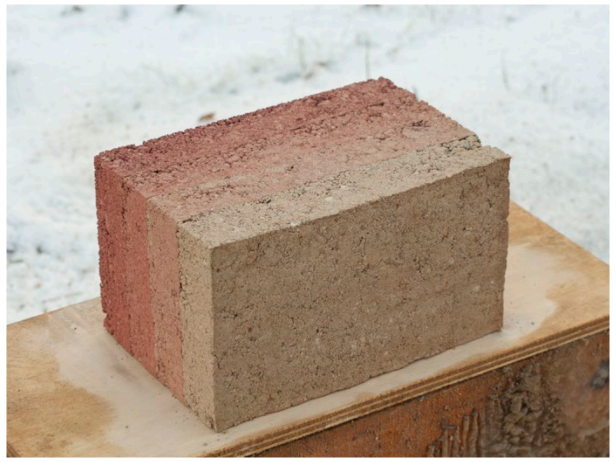


Figure 57. Ready to be butchered.

Figure 58. The uneroded and unpigmented layer.

Figure 59. Deep erosion from the unpigmented to the most pigmented layer.

03 Earth Excursion

To study several rammed earth projects in reality I went on an excursion to Germany, Switzerland and Austria. The company Erden has in some way been involved in all of the projects I visited. In Austria, I also got the chance to visit Erden and discuss with several of the employees and the founder, Martin Rauch. They are the leading experts worldwide when it comes to prefabricated and unstabilised rammed earth constructions.

During the trip, I was able to study rammed earth up close and look at a wide range of different details in the constructions. In the following chapter, I am presenting these observations together with photos.

These are the 10 projects I visited:

– Goldkammer Museum, Frankfurt.
– Alnatura Campus, Darmstadt.
– Zoological Garden Etosha House, Basel.
– Swiss Ornithological Centre, Sempach.
– Ziegelei Museum Kiln Tower, Cham.
– ETH Earth Dome, Zürich.
– Haus Rauch, Schlins.
– Erden Werkhalle, Schlins.
– Erden Haus, Schlins.
– Studio Rauch, Schlins.

Figure 60 (left). Me on top of the Kiln Tower, Cham.

Erosion

Eight of the buildings that I visited had exposed rammed earth on the exterior. All of them show signs of erosion in some way, but in varying amounts and appearances. Haus Rauch and Studio Rauch have protruding ceramic tiles as erosion checks, while the others have lime mortar erosion checks that are flush against the rest of the facade. As seen on the Swiss Ornithological Centre (figure 61), these lime mortar checks can also protrude if the erosion of the earth is deeper. The characteristic horizontal lines from the compacting of earth in layers are still visible below the protecting roof, but these fade away where the facade is exposed to rainfall.

The difference in appearance between uneroded and eroded rammed earth becomes even clearer when comparing the surface inside and outside of the Swiss Ornithological Centre (figure 64).

The stones used in the earth mix of the Swiss Ornithological Centre (figure 62) are brighter than the stones in Studio Rauch (figure 63) and Haus Rauch (figure 65). This means that the eroded areas of the facade are brighter than the uneroded areas. And as the building gets older the facade will get brighter.

As presented in the literature review, the pace of the erosion of a rammed earth facade will decrease over time. This mechanism is evident when comparing the erosion of the Swiss Ornithological Centre (figure 62) and Studio Rauch (figure 63). The Ornithological Centre was built in 2013 and Studio Rauch was built in 1990. Despite this, Studio Rauch is not more eroded than the Ornithological Centre.

However, it should be noted that the amount of erosion depends heavily on wind exposure. The facade of the Ornithological Centre facing the open lake is therefore a lot more eroded than the other facades. The difference in erosion depending on the wind is also evident on Haus Rauch (figure 65). The two walls of the inner corner are both equally exposed without any protective roof, the only difference is the direction they are facing. Strong winds, and therefore driving rain, tend to be more frequent from one of these directions which has resulted in a more eroded wall to the right compared to the left in the picture.

Figure 61 (right). Swiss Ornithological Centre, Sempach.


Figure 62. Exposed brighter stones on the eroded facade. Swiss Ornithological Centre, Sempach.


Figure 63. 30 year old exterior facade with erosion checks. Studio Rauch, Schlins.


Figure 64. Interior and exterior. Swiss Ornithological Centre, Sempach.


Figure 65. The general wind direction has caused more erosion on one side of the facade. Haus Rauch, Schlins.

Prefabrication

Erden is producing prefabricated load-bearing rammed earth elements in their factory, called Erden Werkhalle. I was able to enter the factory and look at the process up close. During my excursion, I also made many observations that I could link to the prefabrication.

The prefabricated elements are produced in several steps. First, their machine distributes earth in a 50 m long formwork and compacts it. This is done layer by layer until the long wall has reached about 1.3 m in height. The wall is then cut up into smaller elements, accordingly to the design of each specific project. The top few centimetres of the wall are also cut off (figure 66), to get a flat surface so that the elements later can be stacked. When the wall is cut up in elements the stones in the earth mix and the lime mortar erosion checks are also cut straight, which can be seen at the Alnatura Campus (figure 72).

As the wall elements dry they get brighter (figure 67), and after 4 - 6 weeks they are completely dry. No firing is needed, and therefore a very limited amount of energy is needed for the production.

Rammed earth walls that are going to be load-bearing are made of elements that are normally about 40-50 cm thick. But it is also possible to make thinner elements, as thin as 7 cm is possible (figure 68). The thin elements are used as an interior wall finish and still have beneficial properties for air quality, humidity control, fire resistance and acoustics. The elements can be cut straight or at a 45-degree angle (figure 69), which is useful when joining two elements at an interior corner. However, it is not suitable to join exterior wall elements at a corner like this, since the corner then becomes more vulnerable to erosion.

The wall elements are transported from the factory to the project site where they are stacked together with clay mortar (figure 70). The joints between the elements are then retouched with the same earth mix as used for the wall elements. At first, the joints are still visible (figure 71), but when the earth in the joints also dries the appearance becomes monolithic, just like how it would look if the wall was rammed on site directly.

It is possible to prefabricate rammed earth elements in any shape. For the ETH Earth Dome (figure 73), prefabricated arched elements were made, which were joined together seamlessly. However, there is an advantage in just producing straight elements since the same machine can be used over and over again then.

One of the largest costs with prefabricated rammed earth is the joint retouching, since it is a craft done manually by hand. For the Kiln Tower (figure 74) they used another system of stacking the elements, where no retouching is needed. Instead of trying to hide the joints, they emphasised them by putting a narrow window in all the vertical joints. For the horizontal joints, the wooden panels that the elements stood on during the prefabrication process were kept (figure 75), eliminating the need to retouch the joints and at the same time functioning as an erosion check.

Figure 66. Fresh sliced rammed earth elements. Erden Werkhalle, Schlins.

Figure 67. The rammed earth element is starting to dry. Erden Werkhalle, Schlins.

Figure 68. Thinner prefabricated elements for interior use. Erden Werkhalle, Schlins.

Figure 69. A rammed earth element cut at a 45-degree angle. Erden Werkhalle, Schlins.

Figure 70. Stacked, but not yet retouched, rammed earth elements. Erden Haus, Schlins.

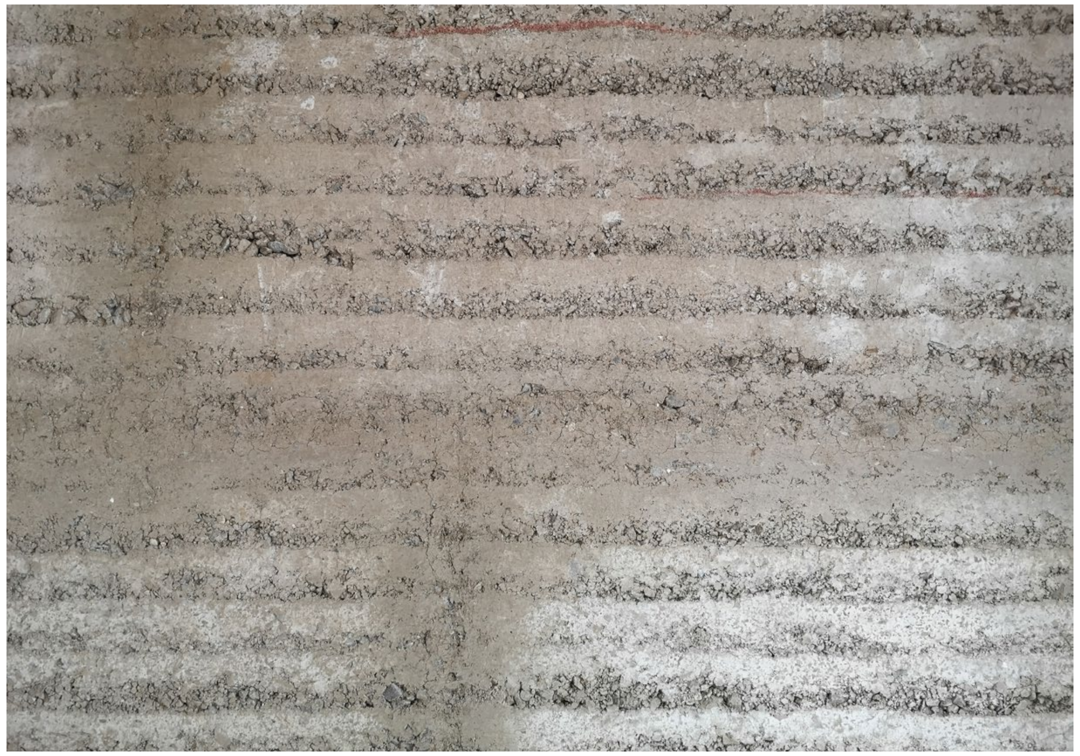


Figure 71. The joints have been retouched but they are still wet, after drying they will not be noticeable. Erden Haus, Schlins.

Figure 72. Where the elements have been cut the stones and erosion checks are also cut straight. Alnatura Campus, Darmstadt.

Figure 73. The rammed earth elements can be prefabricated in any shape and joined seamlessly. ETH Earth Dome, Zürich.

Figure 74. Instead of retouching the joints they have been emphasised with windows and wooden erosion checks here. Kiln Tower, Cham.

Figure 75. The wooden panels that these elements where prefabricated on were kept as erosion checks. Kiln Tower, Cham.

Light and shadow

Rammed earth walls are not particularly reflective at first sight. But at a closer look, it is clear that the smooth clay on top of each compacted layer has a high reflectivity (figure 76). This is mostly true for rammed earth on the interior since the weathered rammed earth on the exterior will get rougher than the interior.

The reflectiveness of the smoother areas of the rammed earth wall emphasises the characteristic horizontal lines. Another way to emphasise the horizontal lines is by using sharp light coming from above and parallel with the wall, like in the Goldkammer (figure 77 & 78). The smoother areas then become lit while the rougher areas have more shadows.

Rammed earth floors can also be reflective since the floor is first polished and then treated with wax, like the floor in one of the rooms in Erden Werkhalle (figure 79 & 80). The appearance becomes very similar to a polished concrete floor or a terrazzo floor.

Figure 76 (right). Interior wall of the Alnatura Campus, Darmstadt.

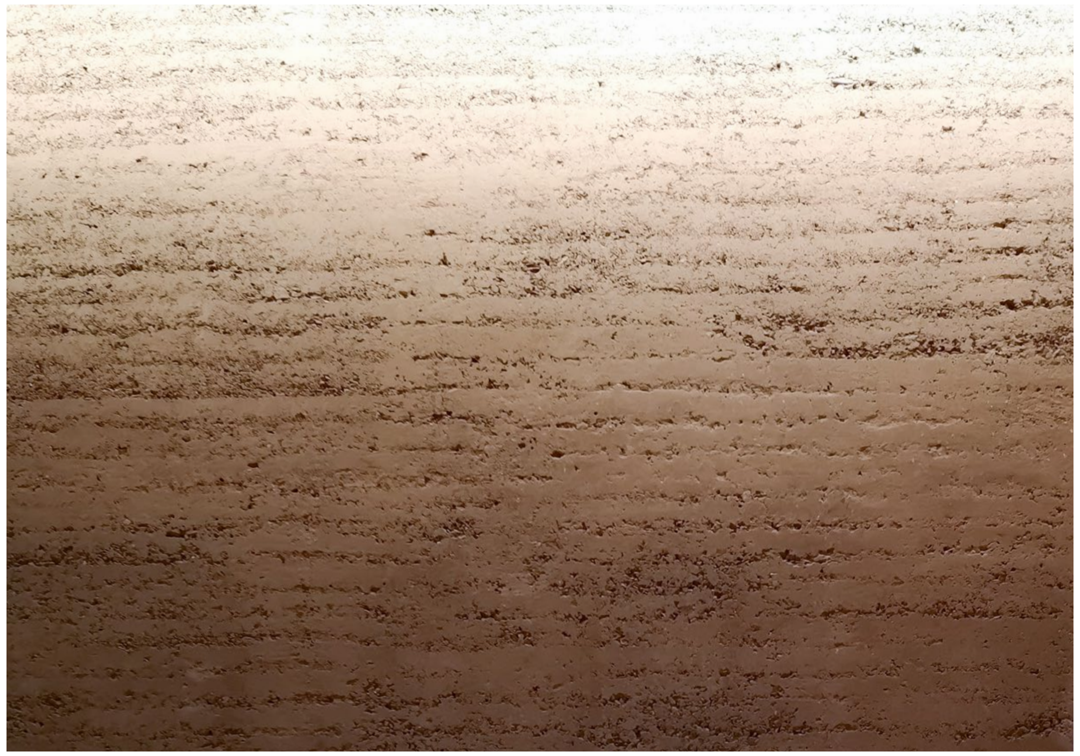


Figure 77. The top light over the rammed earth wall is emphasising the horizontal layers. Goldkammer Museum, Frankfurt.

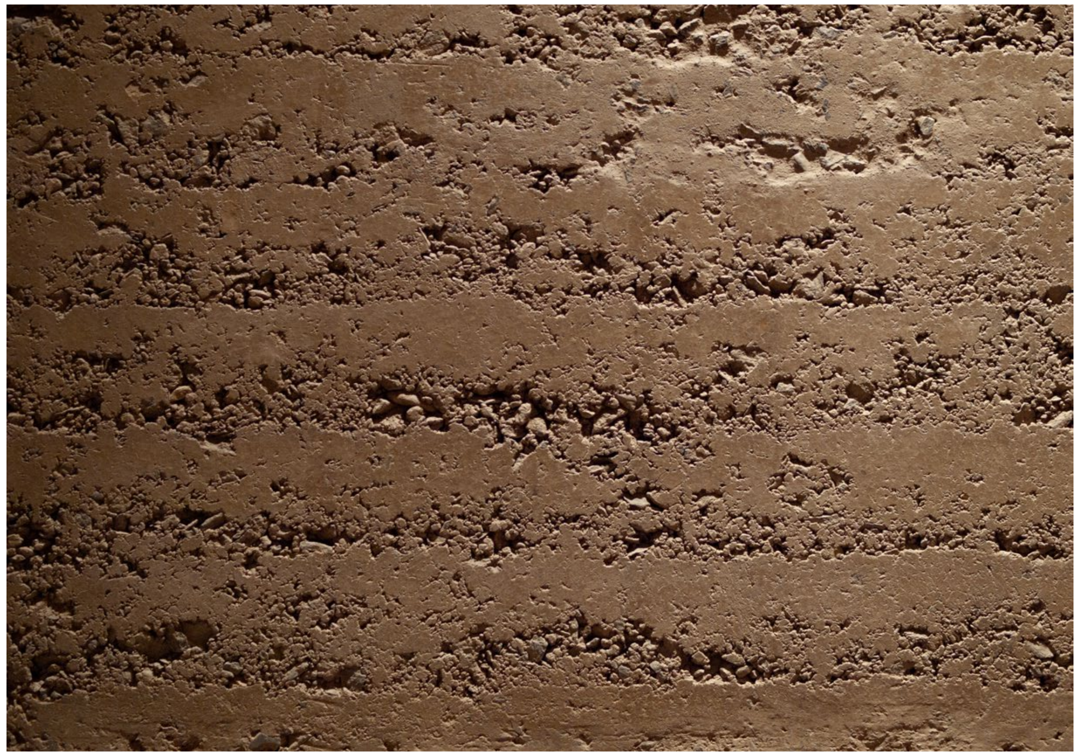


Figure 78. The smoother areas of the wall are highlighted while the rougher areas are in shadows. Goldkammer Museum, Frankfurt.

Figure 79. A polished and waxed rammed earth floor. Erden Werkhalle, Schlins.

Figure 80. The appearance is similar to a polished concrete floor, but this has more roughness. Erden Werkhalle, Schlins.

Details

Similar to how the joints between prefabricated rammed earth wall elements can be retouched, corners of rammed earth walls can also be retouched after construction to make them sharp and durable, as in the Erden Haus (figure 81). If the corner gets damaged in some way, it is easy to repair with the same retouching process. More material of the same earth mixture can simply be added together with water.

In the Swiss Ornithological Centre, many openings seem to have no lintel beam over them (figure 82). Since the earth material over the opening is heavy and the material itself cannot take tension forces, there must be a lintel beam of some kind. Unless the openings are arched, which is not the case in the Swiss Ornithological Centre. Only a thin metal profile is visible over the opening, but that profile is not thick enough to serve as a lintel beam. This means that they must have placed a hidden lintel beam behind the visible rammed earth, likely of concrete or steel.

Another way to solve the lintel beam for an opening is to integrate it into the window frame, like in the office building next to Erden Werkhalle (figure 85), which is under construction. This is also a good example of the combination of earth and wood on the exterior. If the joint between the two materials gets wet, then the earth will absorb the moisture and protect the wood from damage.

A detail that I noticed at the Alnatura Campus is that below the facade there is a patch of stones (figure 83). This is to hide the loose material that erodes away from the facade. The small stones and grains coming down from the facade will then blend with the rest of the stones.

Traditionally, earth and clay buildings have had big overhanging roofs. But as presented in the literature review this is not necessary if the building is built according to the principles of calculated erosion. However, to prevent standing water on the top of the rammed earth wall, a small cover is suitable, like at the Alnatura Campus (figure 84).

A common question is if it is possible to draw installations inside a rammed earth wall. During the trip, I saw many power outlets placed on rammed earth walls with the corresponding installations hidden within the wall (figure 86). So it is possible. It is best to prepare the piping and installations before the construction, but thanks to the possibility to repair and retouch the wall seamlessly it is also possible to add new installations after construction.

There are many possibilities to be creative with what to mix in with the rammed earth. In Studio Rauch there was an object with different pigments and what looked like gold mixed in with the earth (figure 87). And in the Kiln Tower they actually mixed in material from a demolished house (figure 88).

Figure 81. A retouched corner on an interior rammed earth wall. Erden Haus, Schlins.

Figure 82. A thin metal plate seems to support the earth above, but a lintel beam is hidden behind. Swiss Ornithological Centre, Sempach.

Figure 83. A patch of stones is placed below the facade to hide any eroded material coming from above. Alnatura Campus, Darmstadt.

Figure 84. The top of the wall is protected to prevent standing water. Alnatura Campus, Darmstadt.

Figure 85. Instead of having a lintel beam above the window the whole frame is acting as a beam itself. Erden Werkhalle, Schlins.

Figure 86. Yes, it is possible to have power sockets and other installations in a rammed earth wall. Erden Werkhalle, Schlins.

Figure 87. Different pigments and infills can be integrated in the rammed earth. Studio Rauch, Schlins.

Figure 88. Remnants from a demolished house have been mixed with the earth. Kiln Tower, Cham.

Other observations

From these presented images it is clear that rammed earth can have a wide range of different appearances. The appearance depends on the specific earth mixture, what natural pigmentation the earth in the area has, the compacting technique and the weather exposure. There is great potential for architects to explore this further. The wide range of appearances also shows that it is important to make small samples before building something on large scale.

A common concern that I get asked is if loose material or dust will fall off from the interior rammed earth walls. This is not something I experienced during the visits. The walls feel firm and hard and are not affected by touching them. However, an employee at Erden mentioned that it may be wise to vacuum the interior walls once or twice in the beginning, to remove dust from the construction.

During the visit to the various rammed earth projects, I could also notice that the rooms had a pleasant indoor climate and good acoustics. The staff working inside the Swiss Ornithological Centre shares this experience with me. Moreover, I never noticed any unpleasant odour coming from the earth inside.

04
Design Implementation

Using the knowledge I have gained from the literature, the material exploration and the excursion, I have designed a 4-storey residential building with rammed earth and timber as the main structural materials. The ETC buildings by Kaminsky has been used as a starting point for the design, as mentioned earlier. The focus has been stronger on some areas of the building where the material properties are more relevant.

The most appropriate material for each part of the building has been used in the design. Other materials were used when neither rammed earth nor timber were appropriate, for example for the foundation and the windows.

The goal with this design implementation is to show that rammed earth in combination with timber can be used to construct sustainable residential buildings in Sweden with great architecture and living conditions.

Figure 89 (left). The staircase in the designed residential rammed earth building.

Site

An ongoing residential development is located in Östra Kålltorp (Gothenburg, Sweden), with several contractors involved in different stages and areas on the site. The work started in 2018 and will be finished in 2026. Houses in different styles and heights between 4 - 8 storeys will be built. One of the buildings is currently being constructed with CLT timber panels.

On this site I have chosen a currently undeveloped area for my design project. The area is big enough for 4 houses but I have only worked on one design for the building, which can be replicated for the rest of the buildings on the site.

The shallow topsoil on the site has already been excavated. The idea is that excavated earth like this could be used for the rammed earth construction. However, the earth has to come from beneath the topsoil since it should not contain any organic matter. It is therefore unclear if the earth from this specific site would be possible to use because of that. However, this is not a problem since the site is located inside Gothenburg, Sweden's second largest city. There are many other construction and infrastructure projects going on in Gothenburg. All of these generate large quantities of "waste" earth that currently needs to be disposed of in landfills outside Gothenburg. There is a huge potential to use all of this waste material to build with it instead. So, if a prefabrication factory for rammed earth elements would be placed in, or nearby Gothenburg, it could take advantage of all the earth coming out from the city. The waste material could then be upcycled to building material and sent back into the city again.

It is in this scenario I imagine that buildings could be constructed of rammed earth in Gothenburg.

Figure 90. The site is located in a construction area and the topsoil over the bedrock has already been excavated.

Figure 91. Situation plan.

N 1:2500 0 50 100 m

Exterior

The building has exposed rammed earth walls that combine the principles of calculated erosion and the ideas from my material exploration. No erosion checks will initially be visible on the facade after the construction. As time and erosion progress, the facade will get a rougher surface and the hidden erosion checks will start to appear like treasures in the ground. More weather-exposed areas will erode faster, and the pace of the erosion will probably also vary slightly due to inconsistencies in the material and the compacting process. The pace of the erosion will naturally be reduced over time when the outermost layer has washed away, and reduced further due to the appearing erosion checks. Eventually, most of the erosion checks will be visible.

The wooden balconies are separate structures. These are fixed to the facade with slip tie connections that will allow the rammed earth to settle independently from the wooden structure. The balconies also protect some parts of the rammed earth facade from weather exposure, which means that these areas do not need to have erosion checks and that the surface will remain smoother than the exposed areas. The structure also shows how wood can be built with slender elements, in contrast to the thick and heavy rammed earth.

One part of the balconies is open while the other is protected with glass. In this way, the balconies can be used over a longer period of the year and for different functions.

The different properties of wood and earth are shown again at the windows, where wood lintels have been placed over the windows to take the load from the heavy earth above.

The metal roof has integrated solar panels. Since the roof is facing both east and west, the solar panels can be added on both sides.

Figure 92. Facade facing south.

Figure 93. Facade facing west.

1:200 0 1 2 3 4 5 m

Figure 94. Exterior render of the residential rammed earth building showing how the erosion checks has started to appear. Erosion stage 2.

Figure 95. Erosion stage 1.

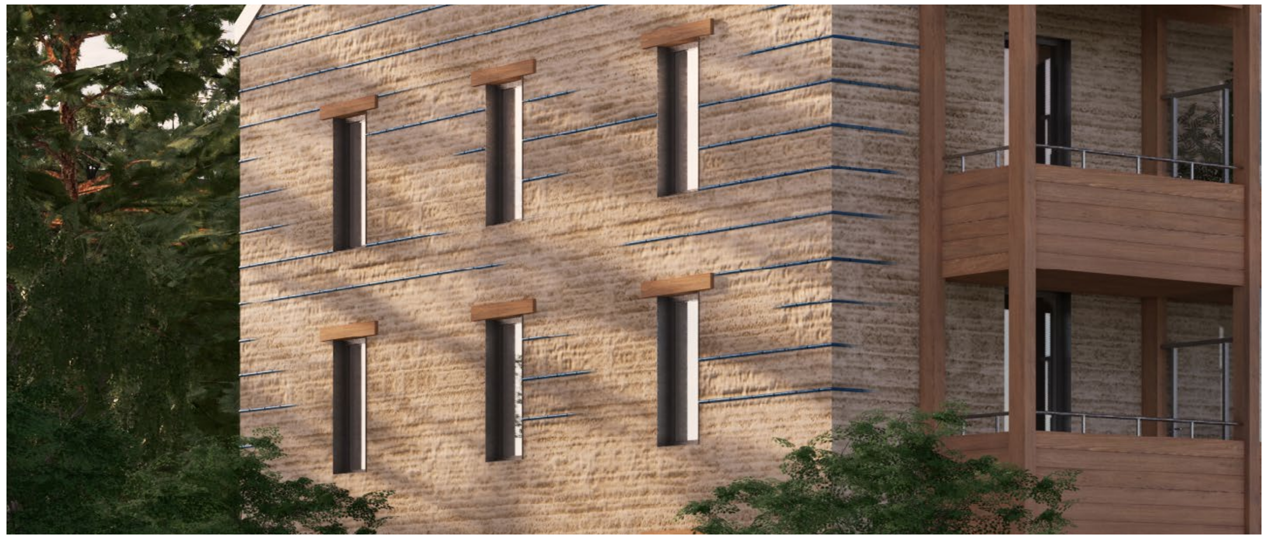


Figure 96. Erosion stage 2.

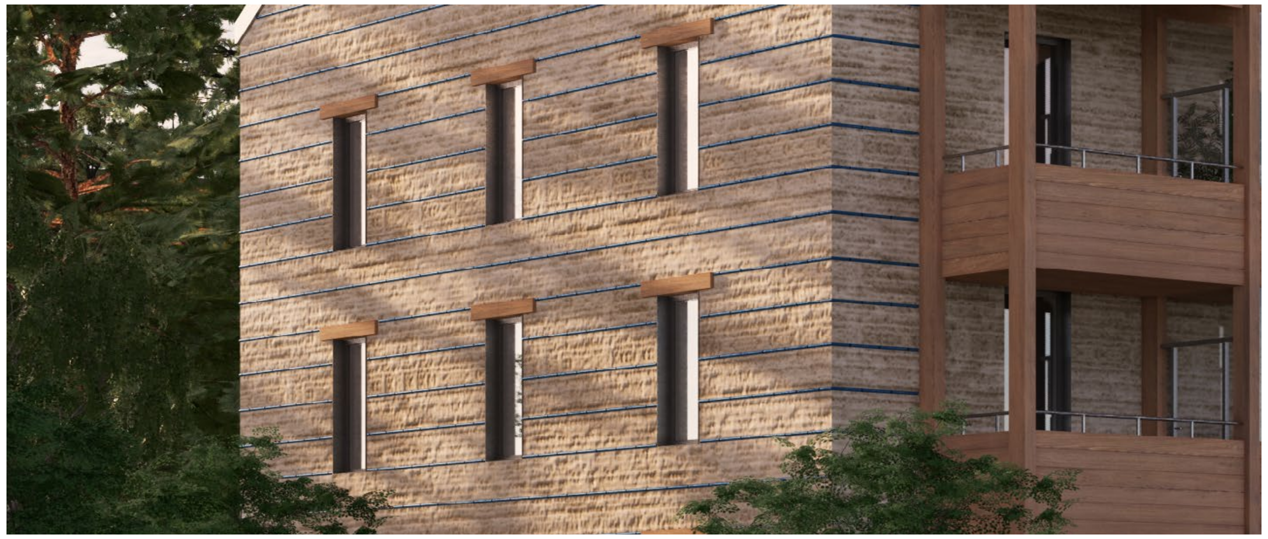


Figure 97. Erosion stage 3.

Floor plans

The floor plans are similar to the ETC buildings in Västerås, but I have made adjustments to account for the properties of the rammed earth walls. The main difference is that the walls must be thicker for load-bearing rammed earth compared to timber. The internal load-bearing rammed earth walls are 50 cm thick, and the external walls are 70 cm thick with 18 cm integrated foam glass insulation, known as Hasopor in Sweden.

The thickness has advantages for fire protection, acoustics and thermal capacity. For example, each apartment is surrounded by a thick rammed earth wall which will limit the spread of fire effectively. The interior walls in the apartments that are not load-bearing are constructed in wood instead, to give the flexibility to change the floor plans.

The rammed earth walls are all connected to each other, this gives extra stability to the building as a whole.

Floor 2 - 4 has four apartments each, in different sizes between one to three rooms. Since the building is placed on a slope, the entrance floor has only one apartment, but also bike storage as well as storage spaces for the apartments.

The elevator and staircase are placed in the centre. Kitchens and bathrooms are located in the centre as well, which will reduce the length of piping and installations. Vertical installations will be integrated into the bathrooms' extra thick walls.

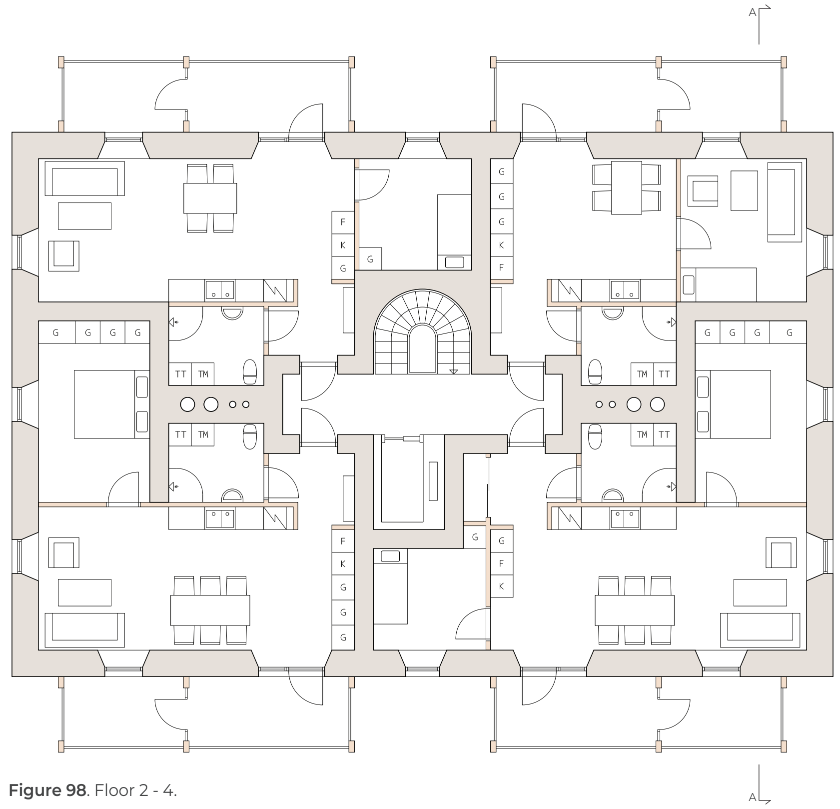


Figure 98. Floor 2 - 4.

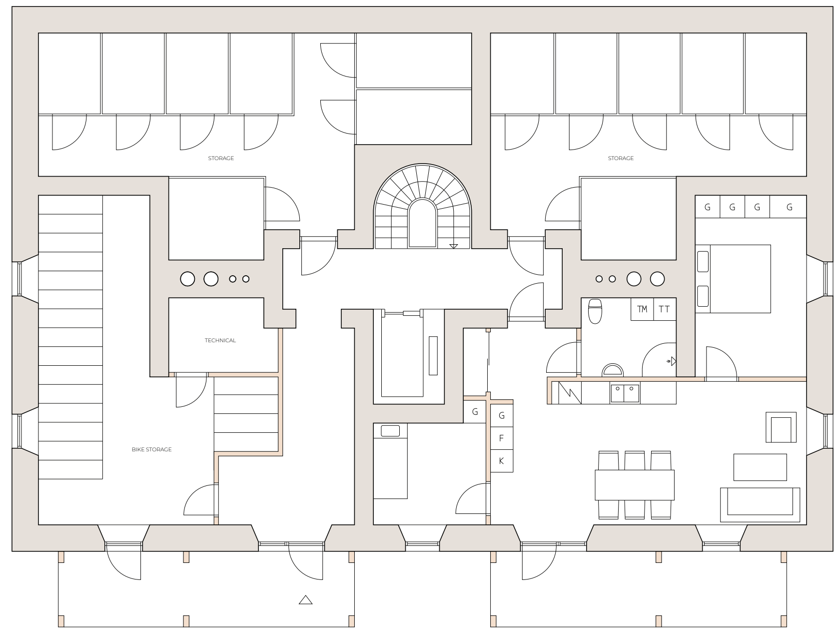


Figure 99. Entrance floor.

◄ N 1:200 0 1 2 3 4 5 m

Section

The rammed earth walls will settle somewhat due to creep deformation. Exactly how big this settlement will be is unclear, but it is in the range of a few centimetres over the whole height of the building. However, this is not an issue because of the way this building is designed. The whole building will settle equally since all vertical load-bearing structure is made of rammed earth, and the wooden balconies are attached with slip tie connections. The roof is supported by a wooden truss structure that is placed on top of the rammed earth walls.

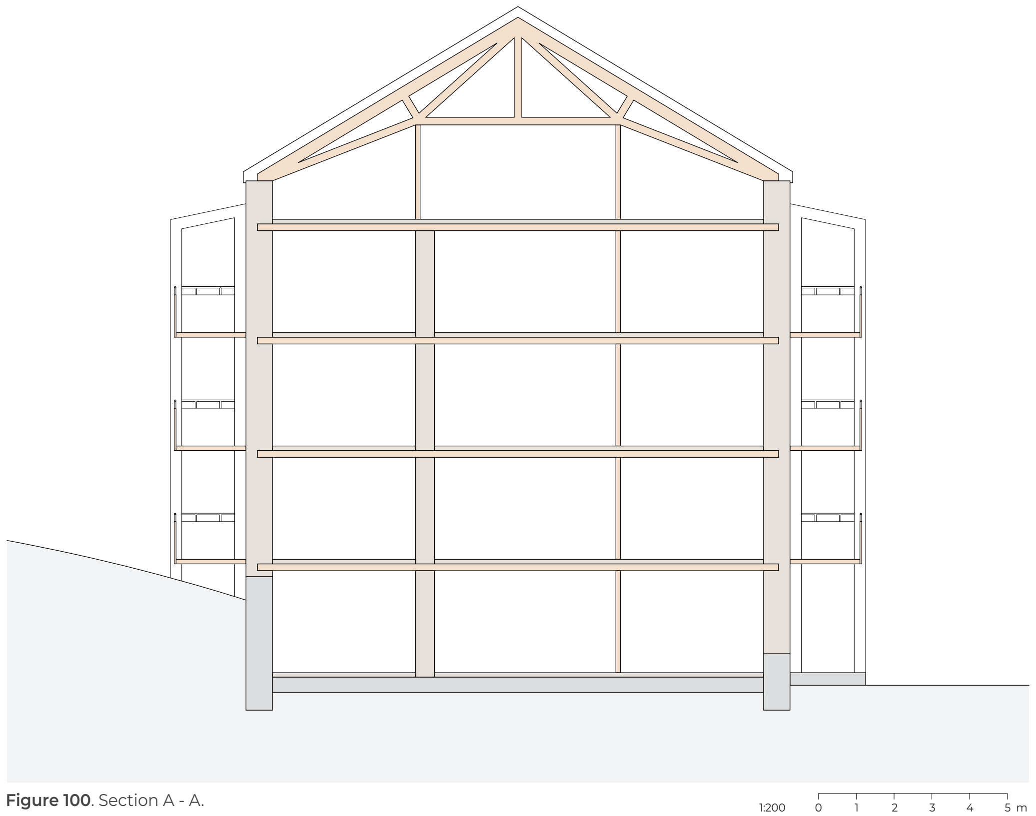


Figure 100. Section A - A.

Staircase

The thick and heavy walls enable the steps of the staircase to be supported on only one side. This is done by inserting each step about 40 cm into the rammed earth wall. A steel box for each step can be rammed into the wall during the prefabrication process to ease this insertion. Since the weight on the inserted part is so large the whole step will be fixed in place. This principle has been used for the staircase in Haus Rauch as well. But in this design, the railing joins each different step, which will help reduce any potential deflection.

The steps will be made of wood with a protective upper surface made of terrazzo polished concrete. The terrazzo will match the polished rammed earth floor in the hallway, but it is probably necessary to add cement for a thin layer like that, subjected to extensive wear.

A roof window will be placed at the top of the staircase. The daylight flowing in along the wall will emphasize the horizontal layering of the rammed earth.

The apartment doors in the hallway next to the staircase will have arched openings. In this way no lintel beam is needed over the opening since the earth is only in compression, and not tension. This arched shape can be created in the prefabrication process by placing an arched solid in the formwork. This solid can be removed when the rammed earth is dry. The rammed earth layers would then still be horizontal, and not perpendicular to the arch which is common for brick arches.

Figure 101. Rendering of the hallway, showing the staircase and an apartment entrance.

The apartments

Rammed earth and wood are exposed in the interior design as well. The CLT-slab is exposed in the ceiling and the floor is of polished and waxed rammed earth. For the load-bearing rammed earth walls there are two options for the surface finish. It could either be left exposed or finished with clay plaster. Which option is chosen could be up to the residents. The clay plaster will be less rough and raw, compared to the exposed rammed earth. However, with plastering comes the option to paint the wall in any desired colour. But after plastering, it may be hard to revert the wall back to the exposed rammed earth appearance. The other interior walls made of wood could also be left as exposed wood or painted if desired.

The residents of the apartments will only be surrounded by natural materials without any potentially harmful chemicals. This will create a healthy and pleasant indoor environment. The apartment will also have good acoustics and humidity level thanks to the exposed rammed earth wall.

Power sockets and other installations are possible to have wherever they are needed, and there are no limitations to what could be hung on the walls. Paintings, shelves and heavy TVs are all possible to hang on the earth walls, but the drilled holes should be deeper than in concrete or wooden walls. Holes in the walls left after something hanging could easily be repaired seamlessly using the same earth that the walls were constructed of.

Figure 102. Interior render of an apartment with a clay plastered wall.

Figure 103 (& next). Interior render of an apartment with an exposed rammed earth wall.

Windows

The windows on the building have a wooden lintel beam above them since the thin window frame itself can't take the loads from the heavy earth wall above. The windows are narrow to reduce the necessary thickness of this beam. The wider openings with a door to the balconies do not have lintel beams since these openings go from floor to ceiling, which means that there is no heavy rammed earth above them.

The openings are tapered to let in more light from the narrow windows. The tapering also emphasizes the thickness of the rammed earth wall. A wooden plate is placed in the deep window niche where pots and plants can be placed.

Some windows are fixed and do not open. These have their frame hidden from the inside to let light flow in unhindered and highlight the wooden ceiling, as seen on the interior render on the previous page (figure 103). However, it should be noted that windows in residential buildings normally are able to be opened, but I wanted to show this possible option since it is a nice detail.

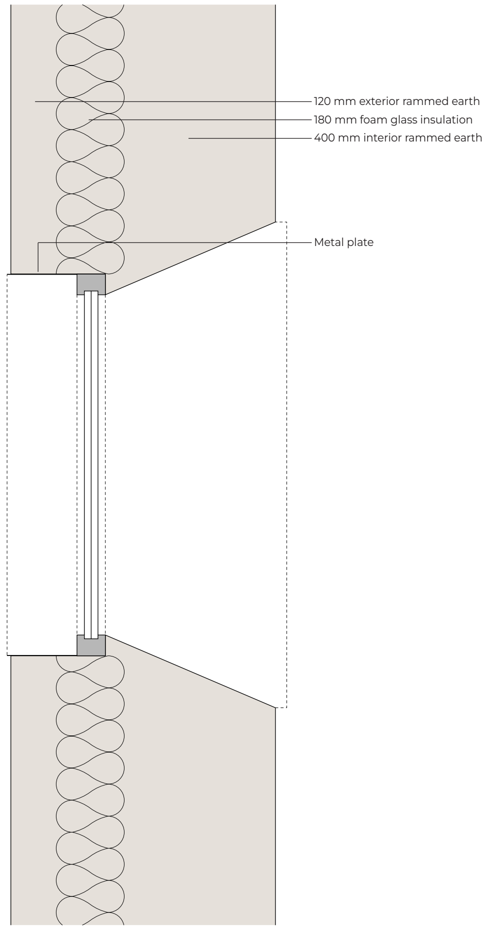


Figure 104. Window, top view.

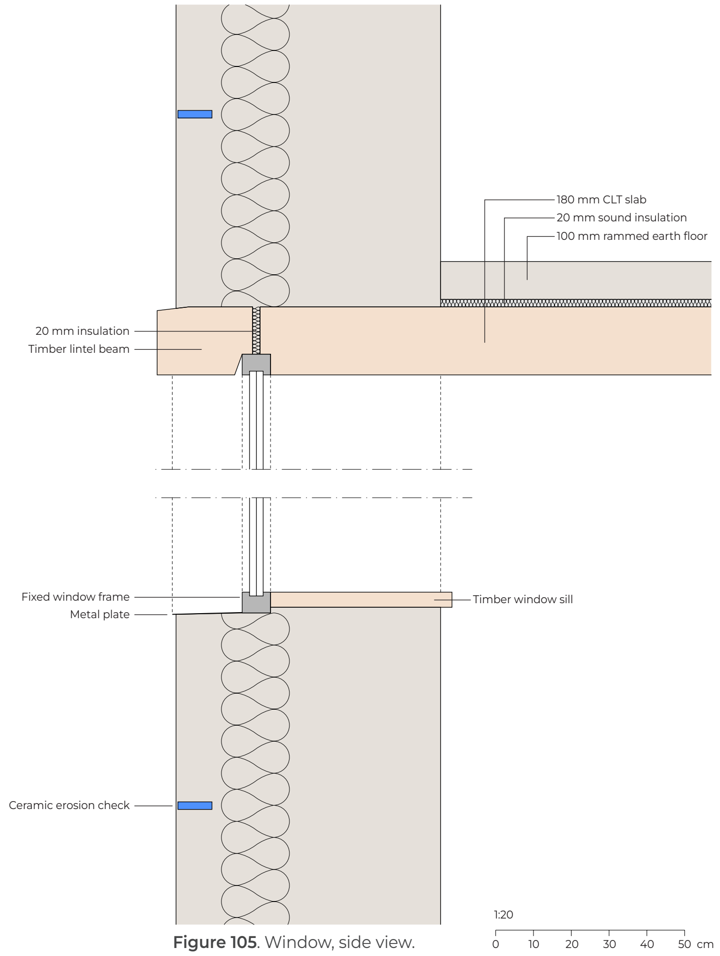


Figure 105. Window, side view.

Floor slabs

Prefabricated CLT floor slabs are placed on top of the rammed earth walls. The maximum dimension of CLT slabs will be 3.5 m wide and 16 m long in Södra's new factory for CLT slabs, which I have visited. The arrangement of the rammed earth walls has been adjusted to support these 3.5 m wide slabs. The slabs will connect the rammed earth walls and stabilise the structure as a whole.

In some newly constructed wooden buildings concrete has been added on top of the wooden slab to handle fire and acoustic regulations. But a rammed earth floor can be used instead for the same requirements without the embodied carbon of concrete. The floor is made using the same material as the rammed earth wall and compacted with a compacting tool. The floor slab may need extra support beneath during the compacting, to avoid excess vibrations. The earth is then polished and waxed to achieve a durable surface and appearance similar to polished concrete or terrazzo. The floor will need some weeks of drying before it is ready to be used.

A sound insulation layer for step sounds can be added between the wood and earth, with different thicknesses depending on the acoustic requirements. This layer can be of a mixture of cork, trass lime and earth as in Haus Rauch (Boltshauser et al., 2011). Piping for floor heating can also be integrated into the earth layer.

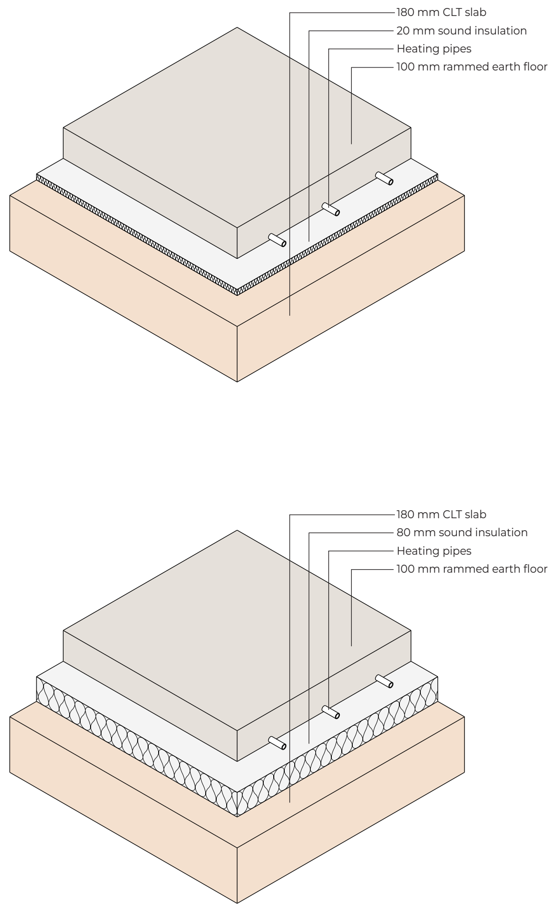


Figure 106. CLT and rammed earth floor construction details.

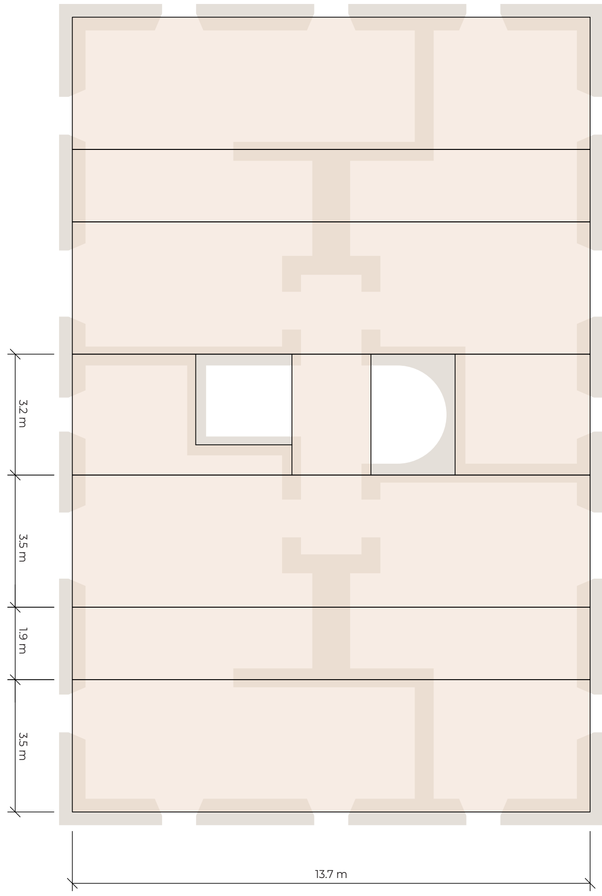


Figure 107. CLT slabs on top of the rammed earth walls.

Stacking system

The exterior rammed earth elements are prefabricated with 18 cm integrated foam glass insulation, like in the Alnatura Campus project. The wall is 70 cm thick in total, with 40 cm of rammed earth inside the insulation and 12 cm outside. No vapour barrier is added. The interior rammed earth elements are also prefabricated, but they are only 50 cm thick and do not have any insulation.

The prefabricated elements are placed on top of each other in a masonry bond, which will increase the stability. The CLT slabs rest on the inner rammed earth layer and lintel beams have been integrated into the CLT slabs where the windows are. The part of the lintel beam visible on the exterior is separated from the slab with insulation to break the thermal bridge.

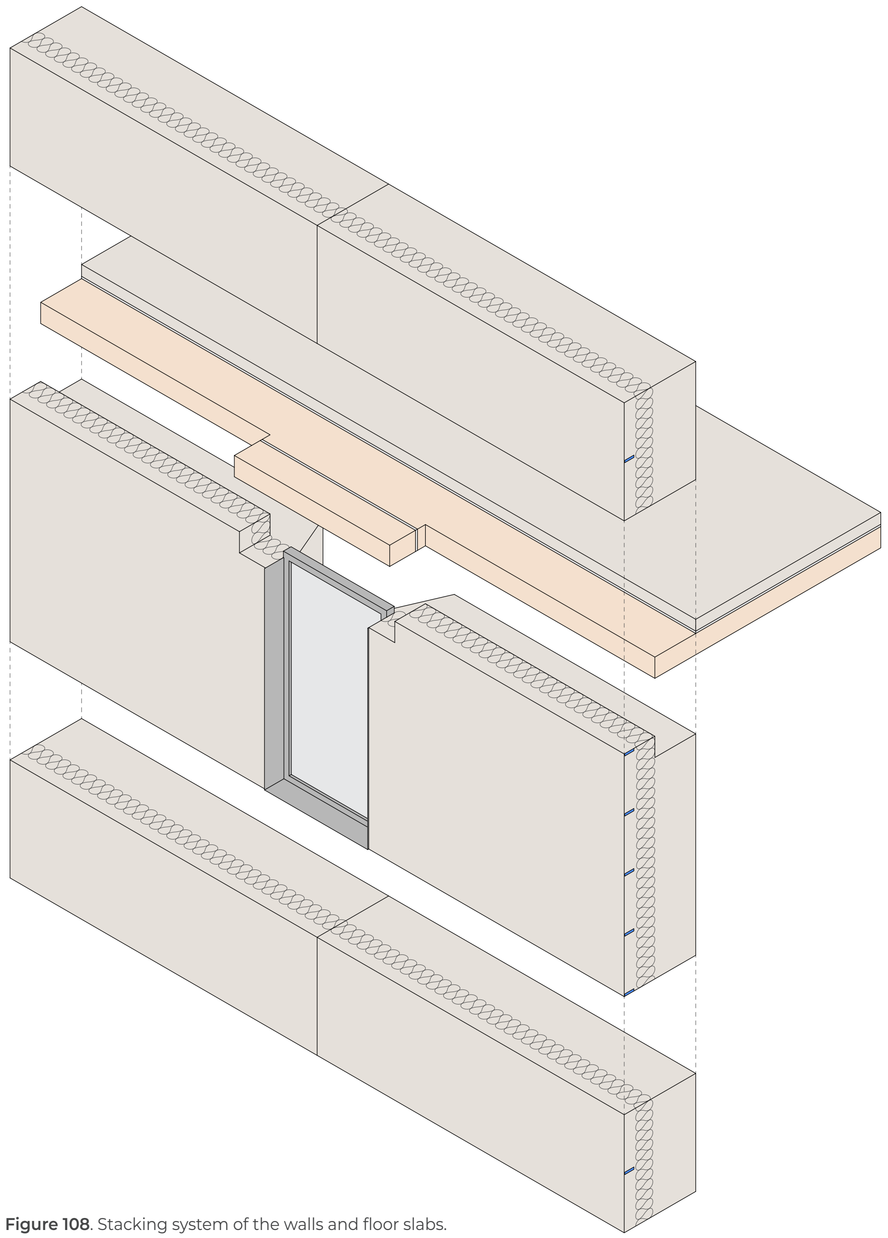


Figure 108. Stacking system of the walls and floor slabs.

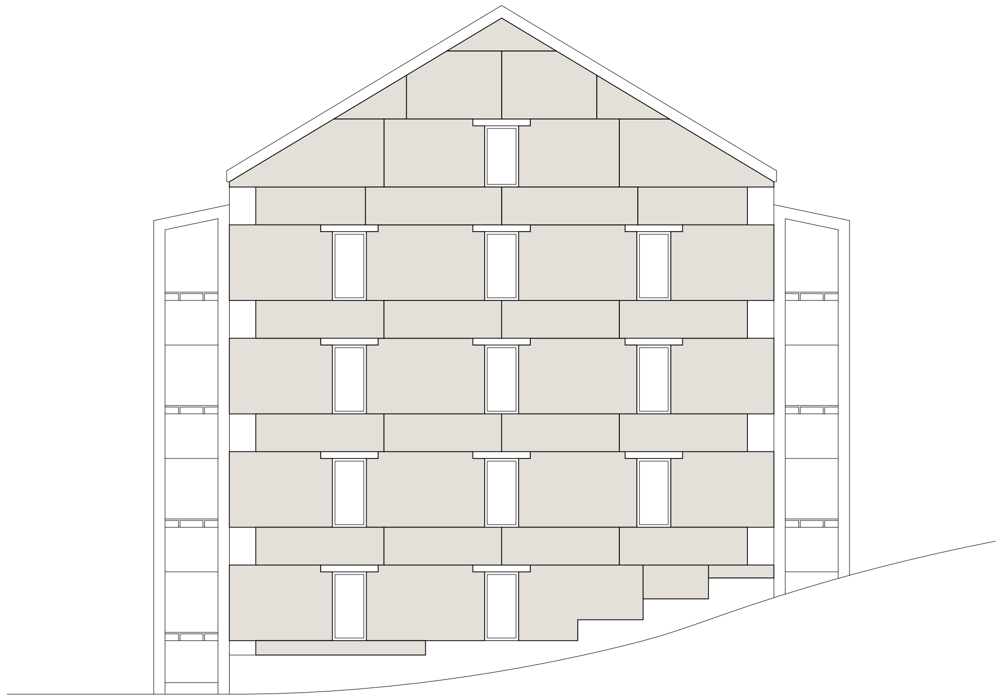


Figure 109. Rammed earth elements stacked. Facade facing south.

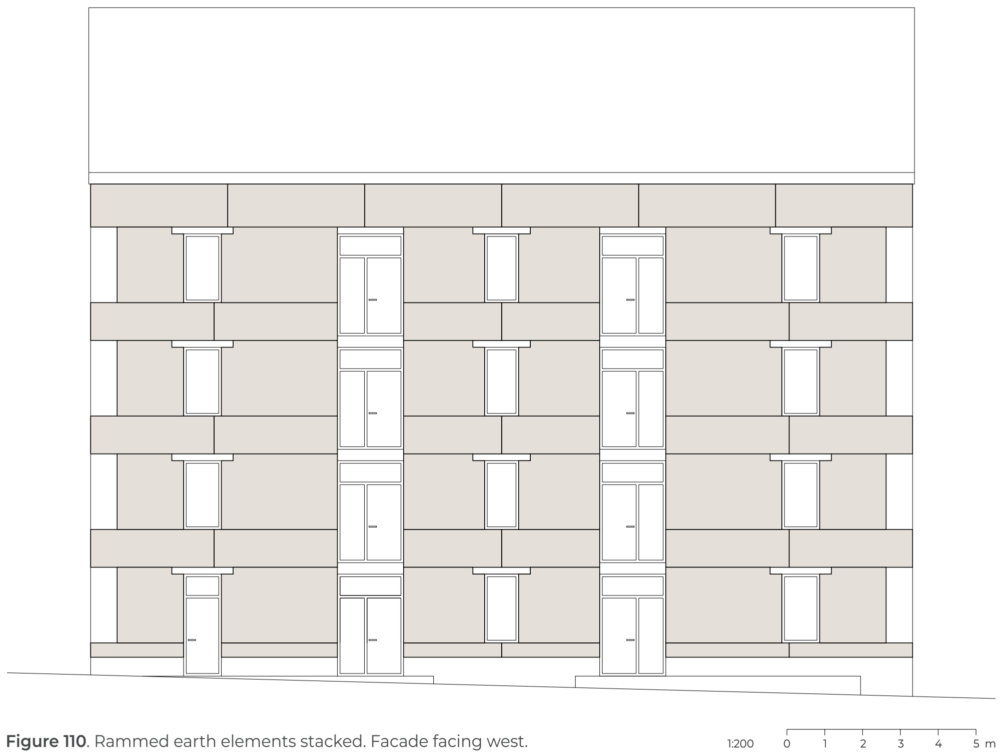


Figure 110. Rammed earth elements stacked. Facade facing west.

Comparison to ETC

The ETC buildings were used as a starting point for the design implementation, as mentioned previously. They were finished in 2021 and are completely constructed of timber. By having used them as a starting point I can now make several observations on how a rammed earth residential building compares to one constructed of timber.

The ETC buildings have different floor plans for each storey, which is not appropriate for a rammed earth construction. Since the walls are very heavy, transfer beams may be needed if the rammed earth walls are not placed on top of each other. Because of this, my design for the rammed earth building has the same floor plan on every floor above the entrance floor. This is also beneficial for the vertical installations, and it is common for residential buildings to replicate the same floor plan all the way up.

The internal structural walls of the ETC buildings are 26 cm thick and the exterior ones are 46 cm thick. Rammed earth structural walls need to be thicker than that, the internal walls in my design are 50 cm thick and the external, including insulation, are 70 cm thick. By implementing the thicker walls, while still maintaining a similar internal floor area, the external dimension of the building gets larger. However, I did increase the floor area of the two apartments facing east, since they felt slightly tight. As a result of this, the internal floor area, excluding structural walls, in the rammed earth building is 10 m^2 larger compared to the ETC buildings. Taking this into consideration, I can conclude that the footprint is 35 m^2 larger for the rammed earth construction, which is equal to 13 % larger or 1 m longer and 1 m wider.

The bigger footprint of a rammed earth building may deter some people from choosing this construction method, mainly because fewer square meters could be sold for an assigned plot of land. However, if the building permit would be regulated by how many internal square meters are allowed, then this would not be an issue. A parallel could be drawn to the limitation of the height for a building instead of the number of storeys. Wooden floor slabs are often thicker than concrete ones, so this regulation affects wooden constructions negatively. If the limitation was for the number of storeys, then wooden and concrete constructions would compete on the same terms. The same applies to rammed earth constructions with the limitation of footprint area instead of internal living area.

It is worth considering what benefits the thick rammed earth walls would bring, and if these could affect the selling price per square meter. Some of these benefits include: unique exposed rammed earth appearance, beautiful deep window niches, great acoustical and fire separation, indoor moisture control and great air quality.

In one way, the exposed timber facade of the ETC buildings and the exposed rammed earth facade are similar. Both will change in appearance over time. The timber will get grey while the rammed earth will get rougher and gradually reveal the erosion checks. The greying of timber is often seen as something beautiful, which the eroding rammed earth also has the potential to be seen as.

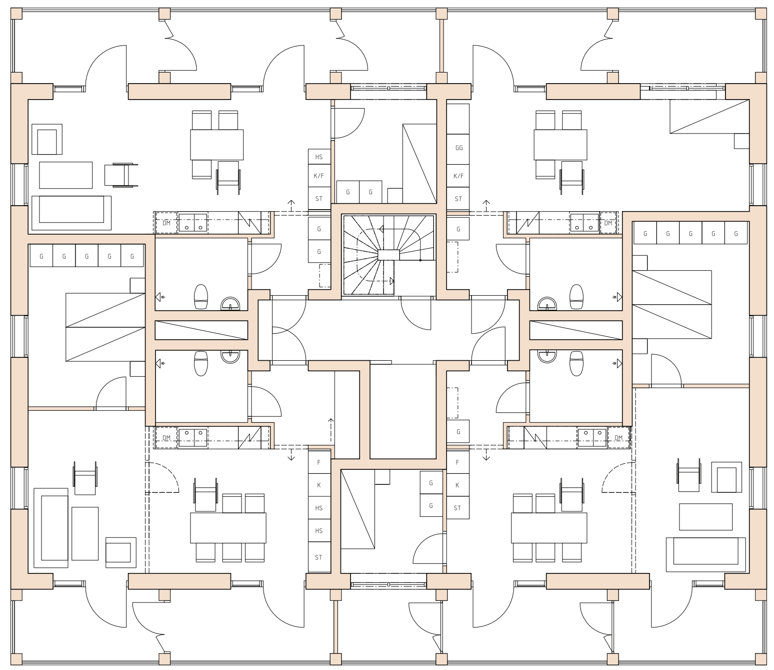


Figure 111. The floor plan of the ETC buildings. Storey 3.

◄ N 1:200 0 1 2 3 4 5 m

Figure 112. Exterior render of one of the ETC buildings.

05 Conclusion

My main objective for this master thesis was to understand the building materials rammed earth and timber - their material properties, architectural qualities and practical applications, on a deep level. And to show how rammed earth is being used today in central Europe.

One year ago, I knew almost nothing about rammed earth, but today I have noticed that I can answer most questions I get about rammed earth with confidence. I gained knowledge about the material by reading, working practically with it and visiting built projects of rammed earth. I still want to explore the material further, but this project has given me a deep understanding of rammed earth. Although, I have not focused as much on timber. My previous knowledge about timber construction was greater than that of rammed earth. But in this project my understanding of timber has also deepened, as I now know how it can be used in combination with rammed earth. I have primarily shown how rammed earth is being used in central Europe today through the literature review and through the observations from the excursion to rammed earth projects.

Two other aims of the master thesis were to answer how rammed earth and timber can be combined to construct a 4-storey residential building in Sweden, and how the erosion of weather-exposed rammed earth facades can be an integrated part of the design.

For the erosion acceptance, I investigated practically a method where the erosion checks are hidden from the start but then reveal as erosion progresses. The erosion checks were glazed in different vibrant colours so that they would stand out even more from the earth when they appear, like treasures in the ground. My hope is that this would signal that the erosion of the facade is calculated and an integrated part of the design, and not something that is harmful to the structure. I implemented this idea in the design of the residential rammed earth building to show how it could look with more context.

The material properties of rammed earth and timber complement each other well, and I used the two materials for different purposes when designing the residential building. The rammed earth is mainly used for the vertical structure since it can only take compression forces. These walls are constructed with prefabricated elements that are stacked to create bigger walls. All the rammed earth walls are also connected to each other to give more stability to the structure as a whole. The timber is used for elements that are in tension, such as the floor slabs and the beams over the windows, and for the slender columns that the balconies are constructed of. Rammed earth is also added on top of the timber floor slab, which complements the timber with better fire and acoustic separation. The existing ETC timber buildings by Kaminsky were used as a starting point for the design implementation. This method gave important insight into how a residential building of rammed earth compares to one constructed of timber.

One of the main insights is that rammed earth buildings need to have a bigger footprint, which may hinder large scale use of this construction method. The price of rammed earth due to high labour costs is another factor that may deter people. Both these factors may however be less concerning in the future if the techniques for constructing with rammed earth are developed further, and if the construction regulations are adjusted to promote the use of sustainable building materials. It is also important to balance the negative factors of rammed earth with the positive ones.

I can conclude that rammed earth is a material with many great qualities, such as acoustical and fire separation, recyclability, low energy need, unique aesthetics, indoor moisture control and air quality. And that it can be used for a variety of different purposes, such as interior and exterior load-bearing walls, floors and interior wall cladding.

Figure 113 (left). Rammed earth wall. Zoological Garden Etosha House, Basel.

Reflection

It was the aesthetics of rammed earth that first got me hooked on this material and made me want to learn more about it. I liked the layering with earths of different colours especially. By the time I was about to start the master thesis my Instagram feed and Pinterest were filled with pictures of rammed earth. But as I started reading more and looking closer at reference projects of rammed earth, I realised that most of those pictures were not showing rammed earth, but rather concrete. Stabilisation of rammed earth with cement is common in the USA and Australia. But what you end up with, when adding cement, is a material that is more similar to concrete than rammed earth, although they still call it rammed earth for branding purposes of course. The problem is that uninformed people will think that this is a more ecological alternative, when in truth it is a marketing lie. I have now learned to distinguish rammed earth with and without cement just from its appearance.

Most of the books I read were connected to Martin Rauch and Erden's work in Austria in some way. He and his company are working with raw earth, without cement. After learning about the two ways in which people are doing rammed earth today I am convinced that the track Martin Rauch has chosen is superior. He promotes the erosion of unstabilised rammed earth as something beautiful, which I agree with. Fear of erosion is one of the reasons why cement often is added, but if the erosion is considered in the design, we can allow for it to happen without problems. To learn more about unstabilised rammed earth and promote the beauty of erosion I decided to focus on this in my project. By studying the erosion of rammed earth, I also clearly positioned myself away from stabilised rammed earth since that doesn't erode in the same way.

The method of inserting erosion checks, glazed in vibrant colours, might help to spread the idea that erosion of rammed earth can be seen as something beautiful. However, if the eroded appearance of rammed earth is still unwanted it is possible to use another cladding material for the building. Timber panels or lime plaster could for example be used as the exterior surface instead. The insulation of the exterior wall can in that case be placed between the rammed earth and the external cladding, instead of as core insulation in the rammed earth.

When I wanted to start working practically with the earth it was not so straightforward. Here in Gothenburg, I had no tools, space or earth. So, I decided that it was a lot easier to carry out the work at my parents' place in Linköping. They have all the tools and a garden I could dig in. However the earth in their garden had not enough clay in it, but the excavated earth that I found nearby was suitable according to my preliminary tests. Although the tests showed a suitable clay content it was still hard to know for sure if the earth mix was optimal or not in other regards such as water, stones and sand content. When I visited Erden in Austria I saw that they often have more and bigger stones in their earth mix. So next time I will try an earth-mix more similar to theirs.

I have also learned that rammed earth is a weather dependent building technique, because when I arrived to my earth storage in the garden one time it was all frozen. So, I had to start with bringing the earth inside the garage to defreeze it. I also carried out all the erosion experiments outside at -12 °C, because I didn't have time to wait for milder weather. This was very problematic because the high-pressure water machine kept freezing all the time. In the end, I took it inside in between all the different tests. My test blocks also froze to the ground, so I had to use a crowbar to loosen them.

The price of constructing with rammed earth may be one of the main factors that deter people from choosing this construction method. The currently high price depends mainly on the high manual labour requirement. As the techniques of working with and prefabricating rammed earth develop, this cost is likely to decrease. The rammed earth production is, so far, also done on a very small scale. Upscaling would likely decrease the price. An advantage is that the raw material, clay and earth, is often completely free and abundant. So, the price of rammed earth depends only on the production. This means that reliable investments in this technique are possible, without risking a sudden price increase. This can be seen in contrast to for example the raw material price of timber and concrete, which have increased a lot recently.

It is worth mentioning that it would be hard to construct a residential building with prefabricated rammed earth elements in Sweden today. The main issue is that

we lack architects and builders with knowledge, and factories for prefabrication. So, the residential building in my design implementation should not be seen as something we can start to build tomorrow, but rather as an insight into what could be possible if we develop the rammed earth technique in Sweden. It might also be wise to start with building something smaller than a whole building, for example an internal wall in a building constructed mainly with other materials.

The idea from the beginning was to investigate both rammed earth and timber and see how they can be combined in constructions. In the end, it is now clear that my focus during the process has been mostly on rammed earth. But this has gradually also become my intention. Mainly because rammed earth as a building material is still very unfamiliar to most people in the field, while timber is not. It has therefore made the most sense for me to investigate and learn more about rammed earth than timber. By spreading the knowledge I have gained from this master thesis I will help to make the field more aware of rammed earth, which hopefully eventually will lead to investments in rammed earth construction here.

Finally, I would like to say that I'm very glad to have had this opportunity to learn about rammed earth, and that I see great potential for it to become a frequently used building material in Sweden!

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Figure credits

Figure 1, 3, 60. © Juan Pablo Ruz Cuen.

Figure 2, 5, 15, 24-59, 61-110, 113. © Tobias Helmersson.

Figure 4. ETC Bygg. Building permit documents, Västerås Ran 2, DP 1842. https://etcbygg.se/material-for-etc-hyreshus.

Figure 6. © Evelyne Delbos. Image reproduced from the 'Images of Clay Archive' of the Mineralogical Society of Great Britain & Ireland and The Clay Minerals Society. https://www.minersoc.org/images-of-clay.html.

Figure 7. © Philip Heckhausen. Pisé - Rammed earth: Tradition and Potential. Page 46.

Figure 8. Erden. https://www.erden.at/Kapelle-der-Versohnung.

Figure 9-12. Erden. https://www.lehmtonerde.at/en/projects/project.php?pID=97.

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