Work Package 3 State-of-the-art Report

Building Materials Development from Excavated Clay

ReCirculate Project

Contents

1 Project Background

The ReCirculate project was initiated to explore new techniques to build our cities. The building materials we use today have a large environmental impact and contribute to climate change both in Sweden and around the world. In order to reduce these negative impacts, there is a need to minimize the extraction of new material and promote materials that already exist and/or have a low embodied energy. Research and innovation are therefore important for developing new material flows and increasing circularity. ReCirculate aims to explore innovative ways of reusing materials and products from demolition and rebuilding projects including the use of "waste clay" as a raw material. New construction products to be explored and developed within the project aim to be used in the construction of Gothenburg City's "fossil-free" preschools and in several other future construction projects. The long-term effect of increased circularity is reduced environmental and climate impact in the construction sector.

Over the next 10 years, millions of cubic meters of earth and clay will be excavated to develop new infrastructures in cities around the world and massive amounts of waste from the deconstruction and renovation of buildings will be created. Currently, there are limited solutions for what to do with these waste materials and how to 'dispose' or use them in a sustainable way. For example, the infrastructure project, Västlänken, in Gothenburg is estimated to produce almost three million cubic meters of excavated clay, and this does not include all the excavation waste which will be generated from the almost doubling of the city’s built environment in the near future. In parallel, waste from construction industry stands for 1/3 of all the waste in Sweden and the yearly amount of waste is approximately 10 million tons. Construction and building companies are at the same time in need of sustainable products to meet the growing global customer demands for healthier indoor environments, decreased climate impact and to meet other regional, national, and global development goals, such as the UN Sustainable Development Goals.

The local administration of the city of Gothenburg (Lokalförvaltningen) runs the innovation project Hoppet, a climate-friendly preschool. The experiences and the know-how from Hoppet aim to be used overall in the City of Gothenburg's own construction projects and communicated to the building sector to inspire and make it possible for others to follow. Within the project Hoppet, materials and systems developed in the ReCirculate project were tested and evaluated.

This report includes a brief overview of selected clay-based products. The report collects and categorizes this information on the state of the art of clay-based products in order to inform possible uses and applications for Gothenburg City’s waste clay, as previously described.

2 Introduction

This state-of-the-art report describes a selection of earth-building techniques/products that have been identified as having potential for reusing waste clay from the building industry; rammed earth (RE), compressed earth blocks (CEB), and clay wall boards and plaster. Each section includes an overview of each technique, composition and properties, example products, and discusses potentials for the ReCirculate project. The report additionally outlines some other techniques/products of interest, that while most likely are further away from being viable in the current Swedish building market, show what additional earth building techniques might be available in the future. Finally, a discussion section summarizes the most relevant info and suggests further areas to explore earth building in Sweden.

2.1 Recent reviews on earth construction

In a systematic literature review Pelé-Peltier and colleagues (2022) identified factors (barriers and drivers) that affect the use of earth material in mainstream construction. Results differed depending on context, such as the economy in a country or whether stabilized/unstabilized earth is used. The most reported barriers were extra costs, lack of codes and standards, lack of skilled professionals, lack of knowledge and awareness and negative perception. The results showed that there is a lack of literature on non-technical aspects such as political, economical, organizational and sociological. Furthermore, the paper calls for two main new areas of research to be developed: 1) Designing training supports for educating all stakeholders, 2) clarifying earthen architectures relation to the circular economy and how it contributes to preservation of natural resources.

Ventura and colleagues (2022) reviewed studies of life cycle analysis on different earthen construction techniques. "According to design choices and local context, earthen construction is not always better than concrete. This means that no universal solution can be recommended with the LCA of an earthen wall."

Giuffrida and colleagues (2019) wrote a paper titled "An overview on contemporary rammed earth buildings: technological advances in production, construction and material characterization". They propose an innovative rammed earth constructive technology in the form of prefabricated elements with a reinforcing timber structure which provides an anti-seismic function.

Rocha & Oliveira (2019) describe the production chain of stabilised rammed earth in Australia. The chain is presented as consisting of three parts: obtaining the material, manufacturing formwork, and expertise of the technicians and constructors. Apart from earth from the building site, earth can be sourced from suppliers of soil and building aggregates. Forms are generally produced by the constructors themselves, either of wood entirely or with a metallic structure. The article compares the Australian method of stabilized rammed earth (stabilised means that it contains cement) with traditional Latin American methods. The main differences are use of stabilization, mechanized compaction and, the manufacturing of the forms. The Australian forms are steel forms which are locked horizontally. The formwork is generally a steel structure with a plywood surface. The prefabricated steel parts are made to standard dimensions. The surface of the plywood is coated with a glass fibre resin which protects it from soil and moisture and makes it easier to disassemble the formwork.

A journal article by Jovanovic and colleagues (2018) describes the characteristics of earth as a building material, presents traditional building techniques and reviews regulations. The authors point out that, while earth building might be the only solution for financially vulnerable populations, it is currently a privilege in developed countries, but mass construction would lower costs.

Gallipoli and colleagues (2017), in a paper titled "A geotechnical perspective of raw earth building" conclude that:

> *If suitably manufactured, raw earth is a viable construction material with low levels of embodied, operational and end-of-life energy. Modern construction techniques have also been developed such as, for example, those employing casted earth or prefabricated earth panels. Further dissemination of these techniques must, however, overcome important obstacles such as the potential inadequacy of local soils, the low durability of raw earth in wet climates and a lack of knowledge about the energy performance of earth buildings during service life. (p. 476)*

In summary the reviews emphasize the environmental potential of building with earth. The state-of-the art varies with local context. One local context may call for a specific use of earth as a building material based on soil type, climate, building codes, economy etc.

3 Compressed earth blocks (CEB)

Compressed earth blocks (CEB) are an earthen building material created by compressing a mix of inorganic subsoil containing clay, with an aggregate, in a machine (manual or automated) to form blocks. The use of CEBs instead of more classic building materials such as concrete, cement, etc. can reduce CO_2 emissions and embodied energy within a structure (A. Ventura et al, 2022). It is common to add stabilizer, such as Portland cement, lime, fly ash, among others to the soil mix before compression for additional CEB strength and resistance to deterioration due to moisture. In that case, the blocks are called "stabilized compressed earth blocks" (SCEBs). The size of the CEB/SCEB units vary based on the form in the press. For example, with an AECT 2001A machine (see table 2), the blocks are 15,2 x 30,4 x 8,9 cm and weigh 8,2-10 kg (Advanced earthen construction technologies, n.d.). The resulting CEB/SCEBs are laid similarly to common masonry blocks to form walls and can serve as the structural system of the building (see figure 1).

Figure 1 *Finca project in Mallorca. Architects: moredesign. Structural walls for the façade with prefabricated blocks of earth Tapialblock®. All made in Mallorca with the earth of the island (www.fetdeterra.com/en/proyecto/moredesign)*

3.1 Production Process

The main steps in the manufacturing process of CEBs/SCEBs are; screening of soil, mixing, and compressing. The goal of screening is to remove both organic and inorganic debris from the soil after excavation. This screening can be done manually with shovels and sieves or with a mechanical sifter. The soil is then mixed to ensure proper moisture content so that the blocks form properly (without crumbling or sticking) in the machine (figure 2). An optimal moisture content ensures optimum compaction and thereby optimal strength for a given mix. During mixing, stabilizers (if used) and water are added to the soil in predetermined proportions. The soil mixture is then placed into an automated block machine or manual press, where it is compressed into a SCEB (or CEB without stabilizer). To create sufficiently strong CEBs/SCEBs, the soil must be placed under approximately 1,500-2,500 psi (10,34-

17,24 MPa) of pressure within the form (Holliday et al., 2016). Blocks must cure/dry before excessive handling, transport, and installation. For example, when portland cement is used as stabilizer SCEBs must cure 28 days before use but can be handled after 14 days (Holliday et al., 2016).

After curing, CEB/SCEBs can be stacked as masonry units in walls. They require a layer of mortar to bond individual units and courses. A clay-based mortar is often used for CEB walls, because a mix similar to that used in the blocks can be used for the mortar slurry (Holliday et al., 2016). A cement-sand mortar is often used for SCEB and may be used for CEBs, but an inconsistent bond between the cement-based mortar and the clay-based CEBs could be an issue.

Figure 2 *Automated CEB machine and blocks drying, OSKAM (https://oskam-vf.com/en)*

3.2 Composition and properties

The literature presents varying compositions and properties of CEBs and SCEBs. This can be explained by differences in local codes and best practice as well as local soil conditions. The following examples present compositions found in scientific literature. Not all the studies specify whether percentages are of weight or volume, but the authors assume that the following percentages are of weight as that is common for laboratory studies. For example, Gutiérrez-Orrego and colleagues (2017) used a 52,8 wt% sand, 0,32 wt% gravel and 47,2 wt% silt and clay (45,6 wt% silt and 1,6 wt% clay), whereas Muntohar (2011) used 20% clay, 33% silt, 47% fine sand soil. Abhilash et al. (2020) used a 41% clay, 12% silt and 47% sand soil, but added sand to obtain a 15% clay soil. Indeed, Reddy et al. (2007) showed that with different clay contents (21,7%, 16,3%, 10,9%, 5,4% and 0%), and different cement contents (4 and 8%), the optimum strength is reached with 14-16% clay. Moreover, the weight loss after 12 freeze-thaw cycles is minimal when the clay content is about 16%. Meaning that a 16% clay content would provide better durability of the blocks. Because of the aforementioned variations a standardized optimal composition cannot be determined. However, there are optimal ranges that can help to guide CEB construction.

In some countries, the building code states an optimal composition for compressed earth blocks. For example, the Peruvian building code, recommends a composition range for unstabilized earth blocks of 10-20% clay, 15-25% silt, 55-70% sand. In the Sri Lankan and Indian building codes, the composition recommended for compressed stabilized earth blocks is 10-15% clay, 5-20% silt, more than 65% sand and gravel with a water content of between 9,5-11% (Bahar et al., 2004). While in Germany, where stabilisers are not used, mixes must be tested to insure the CEBs meet DIN requirements (see table 1).

Table 1 *Compressive Strength Classes (CS) for earth blocks (EB) in accordance with DIN 18945 (Schroeder, 2018)*

Class of block compressive strength CS	Compressive strength MV N/mm^2	Compressive strength SSV N/mm^2
2	2.5	2.0
3	3.8	3.0
4	5.0	4.0
5	6.3	5.0
6	7.5	6.0
Test procedure	DIN EN ISO 7500-1:2004-11	DIN EN ISO 7500-1:2004-11

MV: Mean value; SSV: Smallest single value.

As mentioned, Different stabilizers can be used to improve strength and durability of CEBs (making them SCEBs), however, there is debate about the efficacy and benefits of adding stabilizers. For example,

> *Van Damme and Houben modeled CO2 intensity of earth mix designs by gained resistance (kg CO2 eq/MPa) as a function of cement content. They showed that the binder addition in earth does not increase the resistance to a sufficient level to make it competitive, from an environmental point of view to cement based concrete: kg CO2 eq/m3/MPa seems much higher in stabilized earth construction than for conventional concrete. Thus, the need for using a binder can be questioned as several earthen techniques are available without a binder. However, this study considers that strength is the only function of using cement in earth construction and lack of sufficient consideration for the broader factors needed to make a fair comparison between stabilized earth, unstabilized earth and concrete blocks.* (Ventura et al., 2022)

The most commonly used stabilizer is cement. According to Riza & Rahman, (2015) the optimal cement content range is between 5 and 10%. It is also possible to use 10% lime instead of cement, the lime stabilized blocks are recommended to be used only in single-story buildings (Riza & Rahman, 2015). In at least one study, the combination of cement and lime proved stronger than cement or lime alone, where the maximum strength was achieved with 5 % lime plus 5% cement for soil blocks containing 15% clay and 10% silt, and 7% cement plus 3% lime for soil blocks containing 5% clay and 5% silt (Malkanthi et al., 2020). The use of ash can also improve strength while at the same time potentially reduce the CO_2 emissions of the SCEBs. For example, a combination of lime and rice husk ash would be suitable for SCEBs, with a ratio of 1:1 by weight (Muntohar, 2011). Moreover, fly ash (a coal combustion by-product) can also be used to reduce cement content in SCEBs. With a 15% fly ash content, only 5-7% cement would be required to achieve a compressive strength of 5 MPa (Islam et al., 2020).

According to Minke (2009), CEBs like other earth construction materials are able to absorb and desorb humidity faster and to a greater extent than any other building material, enabling it to balance indoor climate. CEBs also absorb heat and radiate it back to the indoor environment when the temperature drops (Minke, 2009). CEBs have a thermal conductivity lower than fired clay brick, 0,58 and 0,82 W/mK respectively, and have a greater heat capacity than fired clay bricks, 0,85 and 0,80 kJ/kg respectively (Lamb, 1998). So CEBs can be used to regulate humidity and heat in a building. Moreover, CEBs are not flammable (Morton, 2008), they permit good sound insulation, as well as good insect and mold resistance. CEBs compressive strength is generally suitable for building construction, even if it depends on cement content, types of soil (plasticity index), compaction pressure and types of compaction as well as grain and particle size (Bahar et al., 2004). According to Bahar et al. (2004) an optimal plasticity index range of the clay soil for CEB is between 15 and 25%. Nevertheless, CEBs are vulnerable to abrasion and impact loading, erosion and cracking damage, because of water infiltration (Morton, 2008). A big advantage of CEBs is their low embodied energy when compared to conventional building materials (see figure 3). According to Zami & Lee (2010) , building a square meter of masonry with SCEBs would consume 15 times less energy than using locally fired bricks. This can be even less when not using stabilizers such as cement and lime.

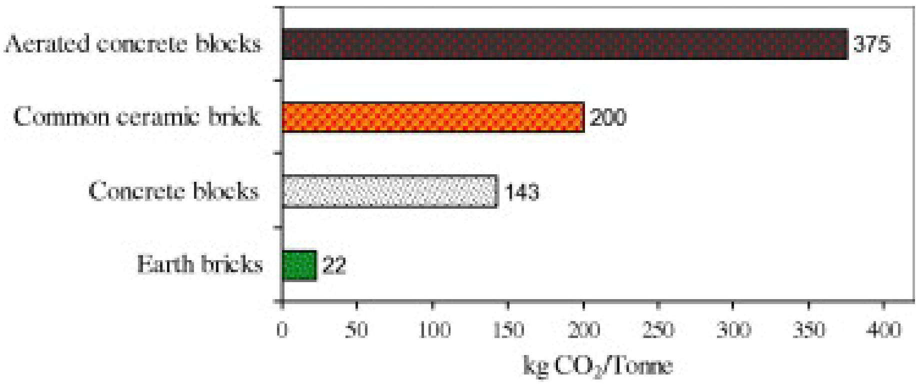

Figure 3 *Embodied energy for different materials (Pacheco-Torgal & Jalali, 2012)*

In a study by Fernandes et al. (2019) rammed earth and CEB were shown to have a total embodied energy of 3.94 MJ/block and 596 MJ/1m3. The Global warming potential was 0.39 kg CO2 eq/block and 47.5 kg CO2 eq./1m3. A cradle-to-gate analysis performed as part of the study showed that the potential environmental impact could be reduced by about 50% by using earthen building elements instead of traditional ones.

Another benefit of compressed earth block is the possibility of doing low-cost buildings, however there is a lack of research and literature on cost-benefit analysis of earth building in the European context. More research and analysis need to be done in this regard to further explore viability. That being said, Zami and Lee (2010) show some examples of cost-benefit analysis in low- and middle-income countries, for example, in an Indian context, 1m² of SCEB masonry has been shown in some cases to be 48% cheaper than extruded wire cut bricks and 24% cheaper than country-fired bricks (Zami & Lee, 2010). The labor represented the major cost (about 45% of the manufacturing cost of SCEBs). Another potential for cost reduction could be in adopting earth shells, especially domes, in association with earth blocks (Bradley & Gohnert, 2018). Costs can be lowered further by not using portland cement, CEBs instead of SCEBs.

Although CEBs are most common in moderate climates, it is also possible to use them in a cold climate. Nevertheless, if the blocks are exposed to freeze-thaw conditions there is risk of damage on account of absorbed water expanding when freezing, adding stabilizers to CEBs has been shown to reduce this risk. According to Mak et al. (2016), the strength for SCEBs with 7,5 or 10% cement isn't reduced after several freeze-thaw cycles, however, the strength for CSEBs with 5% cement is significantly reduced, except if Plasticure (a water repellent) or lime (2,5%) are added (Mak et al., 2016).

Being unreinforced masonry, CEBs are particularly vulnerable to seismic loading and would only be acceptable for use in regions with low seismic activities. If needed, an application of Geogrid (figure 4) has been shown to be a promising method of reinforcing earthen-wall systems (Holliday et al., 2016). However, according to Solomos et al. (2008), seismic activity in Scandinavian countries is low and therefore unreinforced CEBs would be suitable for buildings in Sweden.

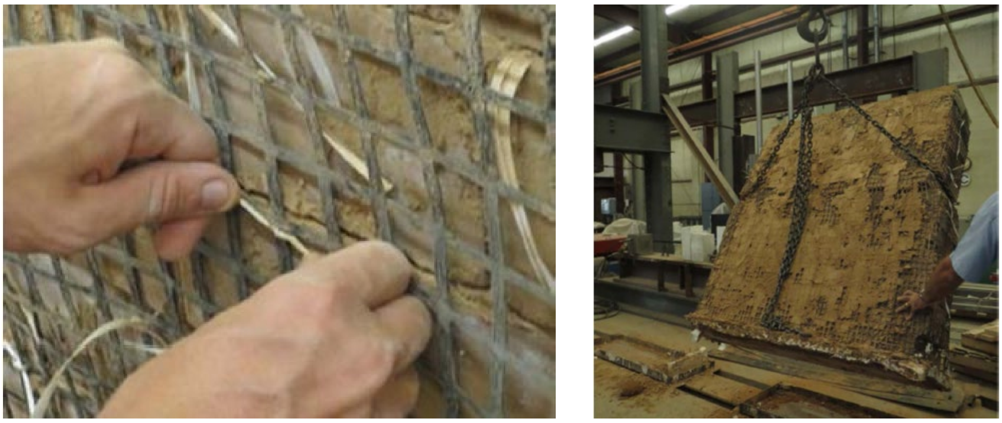

Figure 4 *Geogrid stabilization process and test for CEBs (Holliday et al., 2016)*

Waste materials could be a good alternative for stabilizing and reinforcing earthen structures. For example, 1% of mineral wool waste has been shown to increase compression resistance by 29% and 0,1% sisal fiber to substantially increase tensile strength (Gutiérrez-Orrego et al., 2017).

3.3 Example products

A number of CEB products exist on the market, both machines to create CEBs as well as companies that sell readymade CEBs. Table 2 includes a small selection of CEB machines and Table 3 shows some examples of CEB products.

Table 1 Properties of select CEB machines. (The costs are based on 1USD equals 0,94EUR, sept. 2023)

Model	Company	Weight (kg)	Engine	Block production	Block dimensions (cm)	Approx. Cost (Euro)
 BP714	Dwell earth dwellearth.com	1089	9,8 hp Fuel efficient Hatz diesel rope pull start	120/hour	10 x 35,5 x 18	56096
 2001A	AECT aectearthblock.com	744	7,0 hp yanmar diesel	300/hour	15 x 30,5 x [5-11,5]	46096
BLM-12-8A2 	Earthtek adobemachine.com	680	8 hp gas	120/hour	10 x 30,5 x [5-20,5]	17312

Table 2 CEBs sold by OSKAM company (oskam-vf.com).

Type	Approximate Dimensions (cm)	Approx. Cost (Euro)
		
Unstabilized CEB	29,5 X 14 X 7	1,65 /block
Stabilized 6% lime SCEB	29,5 X 14 X 7	1,85 /block

3.4 Potentials in Project

Compressed earth blocks show a real potential for the ReCirculate project. Indeed, the thermal and moisture regulation properties are important to lowering energy usage. Furthermore, the techniques for construction using CEBs are similar to those used in concrete block and brick, thus masonry workers would not need to undergo much extra training in order to build with CEBs. However, some experiments are necessary to build with this technique. All soils are not suitable, and the precise optimal composition depends on the region. Moreover, it is possible that unreinforced CEBs are not suitable depending on the region and the project site. Stabilizers and other materials improve resistance against erosion and freeze-thaw conditions. A variety of stabilizers are available, but the challenge is to maintain the low environmental impact. Using cement as stabilizer in earthen construction can cause earth to have lower environmental performance than concrete (A. Ventura et al, 2022). Moreover, construction and demolition wastes seem to have potential as an alternative for additional aggregate and reinforcement in earthen mixes and should be explored further.

4 Rammed earth (RE)

Rammed earth (RE) is a technique for constructing foundations, floors, and walls. It consists of a mixture of clay, sand, and aggregate rammed into a formwork. It is possible to use a wooden pole (traditional technology) or a mechanical ram (modern technology) to compact or ram the earth to make a rammed earth wall. The color of rammed earth elements depends on the aggregate and earth used, pigment can aslo be added. A frequent variant of traditional rammed earth is stabilized rammed earth (SRE), in which a small amount of cement or lime is added to increase strength and durability. Walls are built by compacting layers of earth creating a monolithic structure and are generally from 25 to 60 cm thick (Recavarren et al., 2013).

Figure 5 *Rammed earth wall with brick vault Merida, Mexico (earthlabstudio.com)*

Earthen materials are hygroscopic, thus there is a need for some protection from driving rain and extreme sun exposure. This can be achieved in several ways, usually large roof overhangs and raised foundations are standard characteristics of RE structures. In some cases, surface treatments, sealants or protective screens are necessary (M. R. Hall & Swaney, 2012). While this hygroscopicity creates risk for damage to the structure if exposed to extreme conditions without protection it also plays a role in the thermal behavior of RE walls.

> *When an earthen wall is exposed to sun radiations, water contained into pores can evaporate, the water vapor can circulate inside pores towards colder zones and re-condense. Water condensation will release heat, due to water latent energy, and thus increase temperature. This knowledge on thermal behavior of earthen materials allows to expect energy savings during service life of buildings. It has to be considered on LCA studies.*
> (Ventura et al, 2022)

4.1 Production Process

RE walls are built in sections as long and tall as the form allows, usually on top of a cement, stone, or block foundation. After preparing the soil mixture (see next section for more on this) with the correct moisture content it is dumped loose into the formwork. The loose soil is spread in even layers, usually with an uncompacted thickness of between 10 to 20 cm (Recavarren et al., 2013). Each loose layer of soil is compacted within the formwork. Compaction is accomplished traditionally with handheld tools. The layer compaction process is repeated until the top of the formwork is reached. After the last layer is compacted, the formwork is moved horizontally or vertically into position adjacent to and overlapping the previous wall section (figure 6).

Figure 6 *Traditional process for rammed earth (Recavarren et al., 2013).*

The process is repeated until the wall is extended completely around the structure. The compacted soil has sufficient stiffness for building on top of without waiting for curing or drying of the section below (figure 7). New rammed earth must be protected from rain for at least 10 days while it dries and hardens. The drying process of rammed earth and CEBs is faster than that of masonry or concrete walls. Shrinkage usually stops after a few days (Minke 2006). Depending on the local climate, complete curing/drying of a RE structure can be as short as several months or as long as several years. When a new row is started on top of the previously completed row, the formwork placement is always aligned so the vertical joints in the upper row do not align with those in the lower row. A finished rammed-earth wall is sometimes covered in a coat of earth plaster (Recavarren et al., 2013).

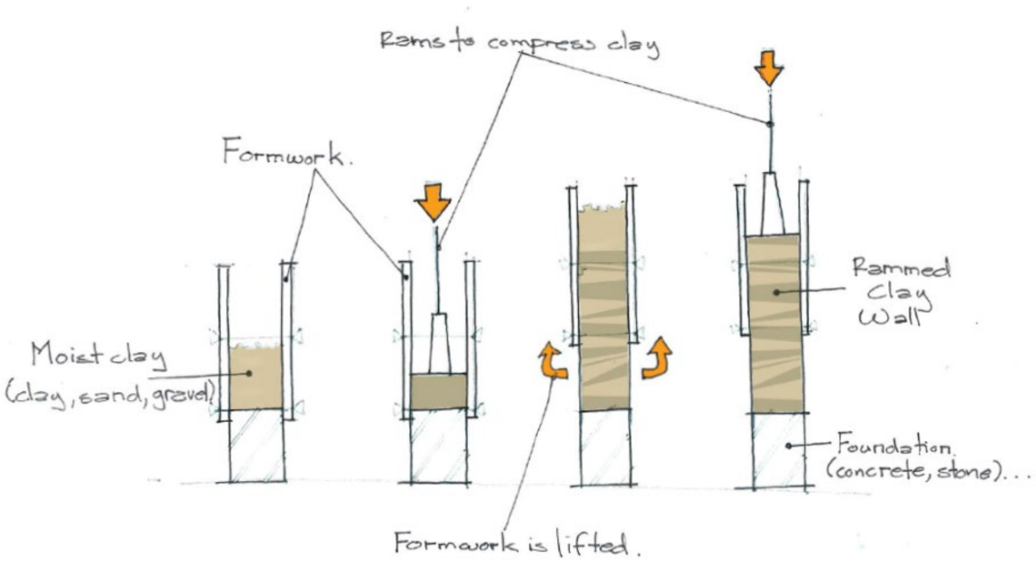

Figure 7 *Drawing of formwork moving to build rammed earth (Escobar, 2013)*

The modern process is not so different from the traditional, the main difference is the use of mechanical equipment such as excavators, bulldozers, pneumatic rammers, etc. The soil is often screen sieved on-site during preparation prior to mixing to remove unwanted debris or large aggregates. It is important to determine the optimum moisture content before the compaction. There are different methods of achieving a uniform soil mix on site such as using rotating-drum mixers type, tractors, etc. Formwork is used as a temporary support during soil compaction. It must have sufficient strength, stiffness and ability to resist pressures caused by the compaction (ramming) process. The form can be removed immediately after compaction. Different types of formworks are available. They may have one side as wide and tall as the wall to be built while the other side is lower and is gradually moved upwards, allowing for access with compaction tools (see figure 8). Alternatively, both sides can be of equal size, and the form moved gradually, vertically and/or horizontally as the work progresses (Maniatidis & Walker, 2003). The rule of thumb for the earth layer thickness after compaction is about 50% of the loose soil depth.

Figure 8 *Rammed earth home being built Yunan Province China, 2023 (Photo: Xingda Guo)*

4.2 Composition and properties

Recommended soil for rammed earth contains about 20-40% clay and silt, and 60-80% sand and gravel according to Gallipoliand colleagues (2017). The authors comment that the exact relationship between soil grading and strength remains unclear, which explains why the recommended ratios are not more precise. There are many variations based on codes and local soil types. For example, the Zimbabwean building code recommends 5-15% clay content, 15-30% silt content, 50-70% gravel and sand content, whereas Silva et al. (2013) recommends a clay content between 5 -20%, a silt content between 10-30%, a sand and gravel content between 45-75% for a soil to be suitable for rammed earth constructions.

Stabilized rammed earth typically contains 7% of weight Portland cement (Hall & Swaney, 2012, p655). Silva et al. (2013) also showed that 7% cement makes a stronger wall than with 3 or 5% cement, and that 13% water content was optimal for compressive strength. According to Jayasinghe & Kamaladasa (2007), an optimal lime content for RE mix is between 6-12% (Jayasinghe & Kamaladasa, 2007). Sodium silicate can also be used as a stabilizer with about 5% content (Maniatidis & Walker, 2003). These are just a few of the stabilizers that have been used in RE mixes. Adding hydraulic binder as stabilizer is still under discussion in the scientific community (Pelé-Peltier et al., 2022) and professionals “prejudicial differences” has been named as a barrier for the acceptance of earth construction in some contexts and regions (Zami, 2022).

The variability of mix ratios, soil properties, etc. makes standardization of earth difficult. A typical unstabilized RE compressive strength can be as low as 1.3 MPa, and as high as 3.6 MPa, if stabilized (either mechanically or chemically), compressive strength can reach up to 12 MPa in some cases (Mustafa et al., 2022). In order to achieve sufficient strength and avoid cracking it is important to avoid using a soil with too much clay (more than 30%). Moreover, any topsoil should be avoided, because topsoil usually contains organic material, which is biodegradable, absorbs water and can be highly compressible (M. Hall & Djerbib, 2004).

Elements built with rammed earth have a high thermal mass. That is why it can be an excellent way to regulate the temperature in buildings (walls absorb the heat during daytime and release it when the temperature goes down). However, the insulation of rammed earth walls is relatively low, and additional insulation is often necessary, especially if air conditioning and heating systems are used in the building (Downton, 2013). According to Narayanaswamy et al. (2020), RE thermal conductivity of rammed earth is 1,14 W/mK with a heat capacity of 698 J/kg K. Moreover, rammed earth is also a good humidity regulator. Rammed earth is an excellent way to insulate against sound because it is a monolithic mass (Downton, 2013) and does not generate the harsh echoes characteristic of many conventional wall materials (brick, concrete block and precast concrete). Tests (CSIRO) reported in *Bulletin 5 Earth-Wall Construction* (Middleton and Schneider, 1987) indicate a sound transmission rating (STC) of more than 50 decibels (STC rating is from 25-65 the higher the value the less noise) for a rammed earth wall of 250 mm (Rammed Earth Constructions, n.d.). Thicker walls, such as standard load bearing walls of 300mm, provide even better sound insulation. A 300mm RE wall has been shown to have a 90-minute fire rating (GreenSpec, n.d.). RE is also resistant to termite damage.

Because rammed earth walls are "monolithic elements" (built as a single element), they give more resistance to earthquake conditions than CEBs. However, rammed earth is still earth material and the resistance to earthquake is relatively low. But like CEBs unreinforced rammed earth is suitable for buildings in Sweden. It is common however to reinforce rammed earth, with a bond beam made of poured concrete, wood or steel, on the top of the walls (Bui et al., 2018).

There is potential to use waste materials in rammed earth. Arrigoni et al. (2017) led experiments to study different aspects using waste materials to replace cement or as binder. 6 mixes were made in this study (table 5, figure 9): a mix with crushed limestone stabilized with 10% Portland cement (mix 1), 2 mixes with a blend of recycled concrete aggregates, stabilized either with 10% cement (mix 2) or with 5% cement and 5% fly ash (mix 3). The three last mixes were made with an "engineered local soil". Indeed, the local soil wasn't suitable for rammed earth, so they used 60% local soil, 30% clayey soil from a quarry and 10% gravel. One of the mixes was stabilized with 5% cement and 5% fly ash (mix 4), another with 6% calcium carbide residue (i.e. a by-product of acetylene gas generation) and 25% fly ash (mix 5), the last mix wasn't stabilized (mix 6). The first result relates to durability, particularly compressive strength and erosion resistance. The compressive strength of mix 1 (about 12,5 MPa) is 1,5 times the compressive strength of mix 2. The compressive strength of mix 3 is 23% lower than that of mix 2, and for mixes 4 and 5 it is even lower. So, the alternative stabilizers performed worse than those using cement. However, the minimum dry compressive strength requirement is 2MPa according to the Australian earth building handbook HB 195, and the first 5 mixes are strong enough. The only one below this value is the unstabilized mix (mix 6).

Table 5 *Different RE mixes proposed in study (adapted from Arrigoni et al., 2017)*

Mix number	Substrate	Stabilizers	Unconfined compressive strength
1	Crushed limestone	10% cement	12,59
2	Recycled concrete aggregates	10% cement	8,73
3	Recycled concrete aggregates	5% cement + 5% fly ash	6,70
4	Engineered local soil	5% cement + 5% fly ash	5,41
5	Engineered local soil	6% calcium carbide residue + 25% fly ash	2,84
6	Engineered local soil	/	1,34

The accelerated erosion test showed that mixes 1,2,3 and 5 have good durability properties. Mix 4 had minimal localized erosion, although mix 6 was completely penetrated after only 30 minutes testing. Without any stabilizer, rammed earth durability is low, and the walls must be protected from rain to avoid erosion. Waterproofing agents, sloping roofs and large eaves are some examples of protection measures.

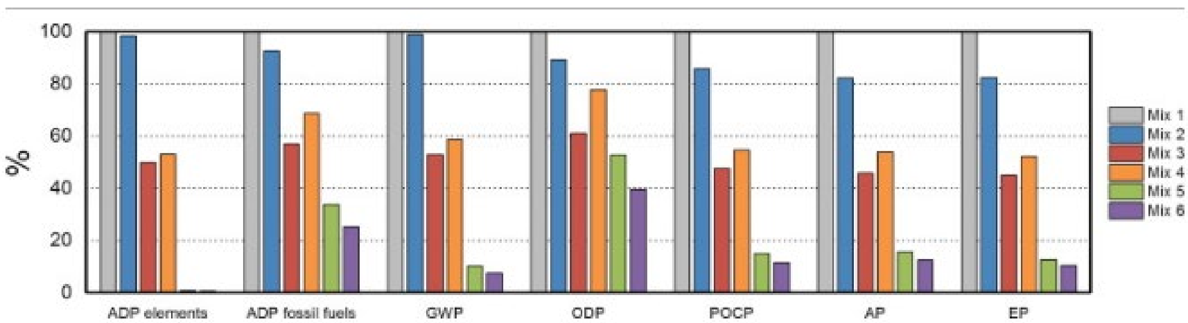

Figure 4 *Life cycle Assessment results for 7 environmental categories. Environmental impact was calculated with the CML Baseline Method with an attributional approach. % is normalized to the base case (Mix 1 in gray) (Arrigoni et al., 2017).*

An analysis of the environmental impact based on European standards for the sustainability of construction works was also led by Arrigoni et al. (2017) (figure 9). The different graphs in the figure above represent the 7 environmental categories proposed by the European standard for the sustainability of construction works: abiotic resource deletion potential for elements (ADP elements); abiotic resource depletion potential of fossil fuels (ADP fossil fuels); global warming potential over 100 years (GWP); depletion potential of the stratospheric ozone layer (ODP); formation potential of tropospheric ozone photochemical oxidants (POCP); acidification potential of land and water (AP); eutrophication potential (EP). The analysis showed that mixes incorporating cement had the highest environmental impact (contrasting mixes 1,2,3,4 with mixes 5,6), the recycled concrete aggregates (RCA) achieved a lower environmental impact than “engineered local soil” in all categories (contrasting mixes 3 and 4). Moreover, the use of alternative stabilizers like calcium carbide residue and fly ash reduced environmental impact by between 50 and 100% per category (contrasting mixes 4 and 5). The most important take away is: eliminating cement reduces environmental impact by up to 85%; and the environmental impacts of unstabilized material and those stabilized with waste products were similar.

4.3 Example products

The company Lehm Ton Erde offers different rammed earth products. For example, the company builds interior but also exterior rammed earth walls, both prefab and on-site, the company offers floors, cladding and stoves (Lehm Ton Erde, n.d.).

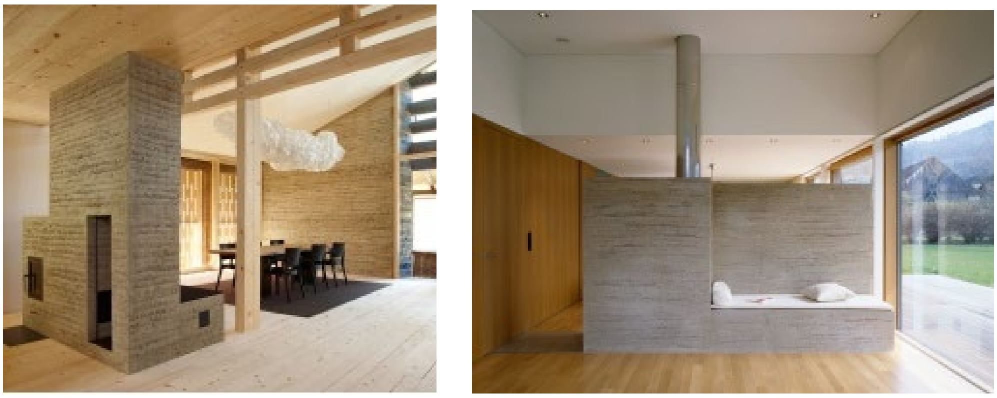

Figure 10 *Rammed earth fireplaces (Source : https://www.lehmtonerde.at/)*

Cost of rammed earth structures is difficult to generalize as so much is dependent on local costs and conditions. As an example of some costs for reference, the Australian company, Earth Structures Group offers the following table on their website (Earth Structures, n.d.). The price per m² depends on the wall height and thickness (table 5).

Table 5 Square meter face price for rammed earth walls by Earth Structures Group. Price in euro is based on the following conversion: 1 AUD equals 0,68 EUR (22-07-25).

Wall height	300mm Thick	450mm Thick
0-3,0 m	480 AUD / 326 EUR	570 AUD / 388 EUR
3,0-4,2 m	600 AUD / 408 EUR	720 AUD / 490 EUR
4,2-6,0m	750 AUD / 510 EUR	900 AUD / 612 EUR

According to Rammed Earth Enterprises (Rammed Earth Enterprises, n.d.), based on the conversion 1AUD equals 0,68€, on average, the price range for a full rammed earth build can fall between 2720 EUR (4000 AUD) per m² to 3060 EUR (4500 AUD) per m² floor area.

> *According to Martin Rauch, in Europe, 1m² of rammed earth cost 100 euro, that is due to the fact the labor wages are very high. Rammed earth is more economical in developing countries in that scene. (Dabaieh, 2014)*

While the principle of rammed earth is relatively simple, utilizing it effectively in a modern building project can be a challenge due to lack of an established supply chain, standards, and practical knowledge amongst stakeholders (Sigurjónsson et al., 2023). Nonetheless there are examples of projects that overcome these challenges. The following case is an example.

Situated in Darmstadt, Germany, the Alnatura office building is the largest one in Europe to have a rammed-earth façade. The design is by haascookzemmrich Studio2050 and the prefabricated rammed earth units were developed by Lehm Ton Erde. Each unit consists of two rammed earth shells with an insulation of 17 cm in-between and the total thickness is 69 cm. The building has a concrete frame and the rammed earth walls only support their own weight. Approximately two years since the completion of the building the west façade had deteriorated by 1 cm (Schoof, 2019). The design utilizes what has been called "calculated erosion": The building is expected to erode relatively quickly during the first few years after which physical features will slow down the process substantially. Horizontal layers of lime ("erosion checks") every 30-60cm will protrude from the surface, slowing down the flow of water down the wall. The same applies to larger aggregates (Kapfinger & Sauer 2015).

Figure 11 *Alnatura campus Darmstadt, Germany (Images: Roland Halbe, Marc Doradzillo, haascookzemmrich STUDIO 2050)*

4.4 Potential in project

The properties of rammed earth make it a suitable material for high energy performance and sustainable buildings. The thermal mass properties of RE give it a high heat capacity, and make it a good thermal regulator, it reduces noise and is fire-resistant. Moreover, being a monolithic element, rammed earth is more resistant to earthquake conditions than CEBs. Nevertheless, compressive strength of unstabilized rammed earth can be quite low and it can be susceptible to erosion. When stabilizers are needed, they should be reduced as much as possible to limit embodied energy. Recycled concrete aggregates such as binder and ashes as stabilizers are promising alternatives to reduce global warming from the building industry.

While expensive, rammed earth has a modern aesthetic, and the finished product tells a story of how it came to being and what it is made of. This quality is valued in projects that want to visually express environmental ambitions.

5 Clay- Boards and Plaster

Clay boards and plasters are often used together with the plaster applied as a finish layer; however, clay plasters can be applied to many substrates. Clay plaster is an earth mortar used to cover interior surfaces and can be used on exterior surfaces but should be protected from the weather, for example with an overhanging roof and by raising it up from the ground. Clay plasters can be applied in one or multiple layers. Dry clay plaster boards are thin clay panels reinforced with reed or fiber; the boards are often covered with a woven jute fabric (Schroeder, 2016).

Clay plaster is usually characterized by the mixture of 3 different elements: Clay, sand, and an organic fiber material. Clay, as in all earth building techniques acts as the binder. There is a considerable amount of chemical variation among the clays. Clay is cohesive and binds to the sand and fiber, holding the mixture together, as well as securing the mixture to the wall (Simple Construct, n.d.). Sand provides structure, strength, and bulk to earthen plasters. Sand is composed mostly of quartz and is a non-reactive substance. Sharp-edged sand is to be preferred as it displays higher interlocking resistance within the soil skeleton (Schroeder, 2016).Fibers form a reinforcing meshwork in plasters, which helps to hold the plaster together, It also provides some flexibility to a dried plaster, when clay dries it shrinks and tends to crack, but this cracking can be countered by the fiber. The fiber used in plasters must be clean, dry, and mold-free. The most used are dry straw, hemp fiber, cattails, coconut fiber, and animal hair (Webb, 2017).

5.1 Example products

Claytech in Germany offers three types of clay boards shown in Table 6 (Claytec, n.d.).

Table 6 *Types of clay boards from Claytec*

Model	**Description**
Clayboard D20	Drywall board made of clay and reed for cladding of wood and metal post structures of inner walls, facing shells, ceiling and roof surfaces.
Clayboard heavy	Drywall board made of clay for cladding of wood and metal post structures of inner walls, facing shells, ceiling and roof surfaces.
Clay dry plasterboard	Dry lining panels made of clay and reeds for local cladding of wood and wooden materials as well as old plasterwork and solid materials.

In the UK, Back to Earth offers two types of clay panels (Back to Earth, n.d.). These are shown in Table 7.

Table 7 *Types of clay boards from Back to Earth*

Model	Description
Easy-to-cut EBB Clay boards	An alternative to gypsum plasterboards
Clay radiant heating panels – Argillatherm Riviera	A part of the Argillatherm radiant heating system. Should be fixed back to a continuous timber substrate. Has routes for pipes.

Clay plasters are fairly common and accessible in Sweden and there are a number of companies that provide plaster products, one Swedish producer and supplier is Målarkalk (www.malarkalk.se).

5.2 Potential in Project

Wall boards and clay plaster can be easier to apply in modern construction than rammed earth and CEBs. They are not loadbearing and should therefore not require the same attention to measuring compressive strength and potential design challenges related to the loadbearing structure. Furthermore, clay boards and plasters have similar hydroscopic properties to those of CEB and RE and can more readily be used to improve indoor climate in buildings since these techniques are usually applied to 'standard' wall assemblies which makes it easier to meet current Swedish codes and regulations. In Germany, clay boards and plaster are more widespread and common than rammed earth and CEB and in Sweden there is some building with clay boards and plaster but almost no RE and CEB.

6 Other Techniques/Products

This section briefly highlights a few additional earth building techniques that are less well known and/or relevant to the project, however, they are included to give some indications on where the earth building industry is headed.

6.1 Poured Earth & 3D Printed Clay

With concerns over increased concrete use and an increased focus on finding environmentally friendly concrete alternatives naturally sourced clays seem an appropriate area to research as they can often be harvested locally, reducing carbon footprint and embedded energy (Bajpayee et al., 2020).

These 2 different techniques, poured earth and 3D printed clay, generally have similar requirements as both usually include a mixture of clay-based soil, and some combination of admixtures (i.e. plasticizers, accelerators, stabilizers). The mix varies widely and, as with the other techniques, the stabilizer has been a cement or lime additive. They differ in that with poured earth, the mix is poured into a formwork similar to concrete and left to cure and harden while a robotic extrusion system is used for 3D printing.

To decrease environmental impact with these techniques and thus make them viable to be a sustainable building alternative it is necessary to minimize the use of cement as a stabilizer. There has been ongoing research into the use of alginate, a seaweed-based biopolymer, as an alternative to cement. For example, as shown in figure 12 researchers at the University of Lyon, France, have been doing experiments studying the feasibility of the use of poured earth concrete stabilized with biopolymer for 'low wall manufacturing' (Pinel et al., 2021).

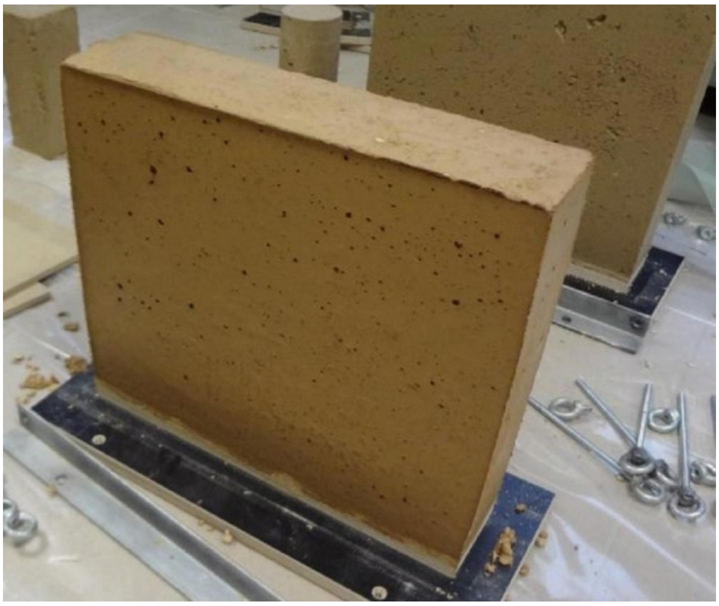

Figure 12 *Poured Clay Concrete low wall demonstrators* (Pinel et al., 2021).

There are also companies like Materrup in France, miga / ACTYVA in Spain and Oxara in Switzerland, providing services and continuing the development in formulating and producing poured earth (clay-based concrete), in particular working with soil from excavations (Building Impact Zero Network, n.d.).

The use of biopolymers for stabilization for mixes used in additive manufacturing processes is also being explored and tested as seen in figure 13, researchers from the University of Bretagne testing an alginate and other hydraulic binders in 3D printed clay applications.

Figure 13 *View of the 3D printer used by the University of Bretagne* (Perrot et al., 2018).

While the cutting edge of clay-based 3D printing is focusing on finding alternatives for cement stabilizers and mix optimization. There are also examples of additive manufacturing using a cob-like mixture. Cob differs from clay in that fiber is added to the mixture in order to improve the mechanical properties of earth walls (Hamard et al., 2016; Keefe, 2005, as cited in Gomaa et al., 2022).

The WASP Company (World's Advanced Savings Project) is an Italian company which was created in 2015 with the launching of a 12-meter-high 3D printer (see figure 14). In 2018, WASP together with Rice House created the first 3D Printed earth house in the world, Gaia. It was 30 square meters, took 10 days and printed entirely on-site from a mixture consisting of 25% soil taken from the site (30% clay, 40% silt and 30% sand), 40% chopped rice straw, 25% rice husk and 10% hydraulic lime. The voids in the walls were also filled with Rice straw for insulation (Gomaa et al., 2022).

Figure 14 Printing process and the house that was built (December 2018 Gaia 3D printed earth house with Crane WASP Presentation)

Another way of increasing the strength of poured earth is to use activated (calcined) clay. Activation of kaolinitic and montmorollonitic clays can be achieved by heating (600 - 800°C), while illitic or chloritic clays, which are more challenging to activate, are more successfully activated mechanically, through repeated impact in a ball mill. A recent RISE report covers the state-of-the-art about activated clays in concrete from a Swedish perspective (Mueller et al., 2021).

6.2 Wood-Earth Hybrid Floor

With the increased interest and production of high-rise wooden buildings there is a need for added weight to build taller buildings. Currently concrete and cement are used to add to this weight but there have been developments in finding alternative lower embodied energy solutions. One such investigation is from Trummer et al. (2022) where they designed and tested a digitally fabricated hybrid cross laminated timber-earth floor system.

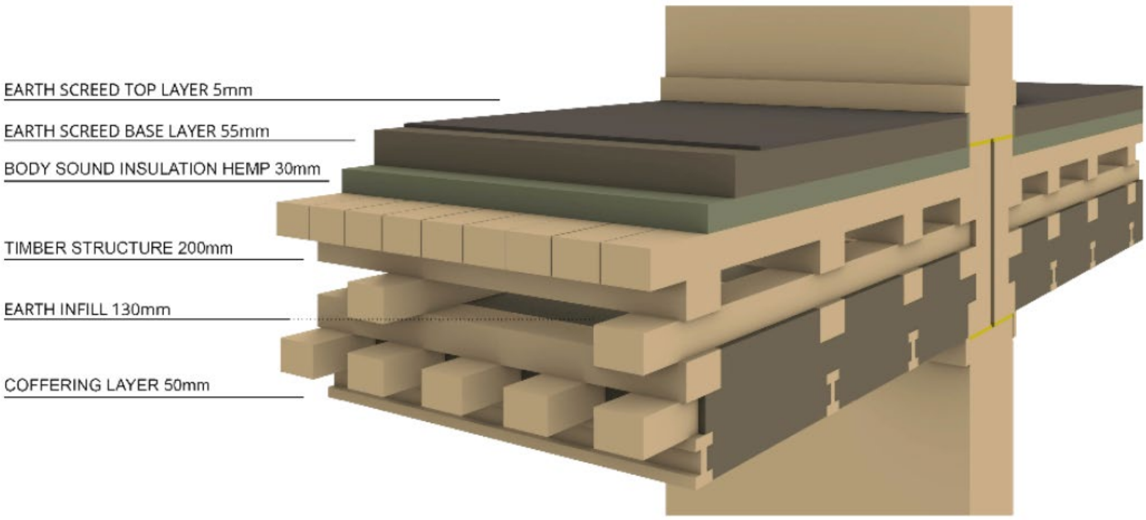

Figure 15 Digital Model of CLT/earth hybrid floor system (Trummer et al., 2022)

The design combined a load-bearing timber structure with an earth infill. The earth provides fire protection, sound insulation and thermal mass. The research project tested using robotic arms to cut and assemble the wood structure using a digital model (figure 15). The density of the wooden structure did not allow the use of a more traditional rammed earth technique therefore poured earth was used. The timber structure utilized cross-laminated timber to minimize the overall wood consumption. The system was verified in three 1:1 scale 4-point bending tests with a limited span of 3 meters (figure 16).

Figure 16 *three prototype Hybrid floor slabs with earth infill (Trummer et al., 2022)*

7 Discussion

When building with earth, the suitability depends on types of soil and availability. When the local soil is suitable and used to create earth building elements, it has the potential to reduce the embodied energy, global warming potential in comparison with conventional building materials (fired bricks and concrete) by restricting material transport and reducing energy use in production. Moreover, earth building elements have beneficial properties such as thermal mass, moisture regulation, fire-resistance, and sound resistance. If the local soil is not optimal, stabilizers might need to be added although this is not ideal as the most common stabilizer, cement, has a large negative environmental impact. The last important thing to consider is the weakness of earth against driving rain and exposure to moisture. Earth structures should therefore be designed properly to mitigate this.

All the earth techniques described in this report seem to have potential in the Swedish building market. However, according to the data found for the state-of-the-art report, it seems compressed earth blocks may be better than rammed earth to begin with in Sweden on an industrial scale as the process has the potential to be less labor intensive, the skills needed are similar to those that already exist in the masonry industry. Clay plaster is another technique with high potential as it can contribute with moisture buffering (a main quality of clay construction) without challenging projects and designs in terms of structural and hydroscopic questions, which may require additional engineering associated with novel building techniques.

Another interesting technique that deserves further exploration is poured earth/3D printing. This technique is still in its infancy, but this also provides an opportunity to develop the process and techniques - so that they align with the Swedish building industry needs and standards - and collaborate with the few companies and researchers that are already working with this.

7.1 Suggestions for continued work

A specific area of application – a construction detail – involving clay, should be determined in collaboration with a building company. Thereafter a prototyping step followed by realization of a built project with industry collaborators. Such a project should generate research data on both technical as well as organizational issues. Technical questions would include; finding optimal composition for the soil used on the project site, the optimum moisture content, the types and contents of stabilizers used, if recycled waste could be used or not. Moreover, tensile and compressed strength, fire resistance, acoustic properties are some important properties the prototyping step should determine. Organisational issues would include division of roles and responsibilities (who certifies what and who delivers what?), communication between stakeholders, knowledge gaps (professional and general), market aspects (supply, demand) and understanding how code and regulations can enable upscaling of earthen construction, involving authorities such as Boverket or SiS.

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