Applications of earthen shell structures

Exploring the synergy of material efficient shell structures and earthen construction

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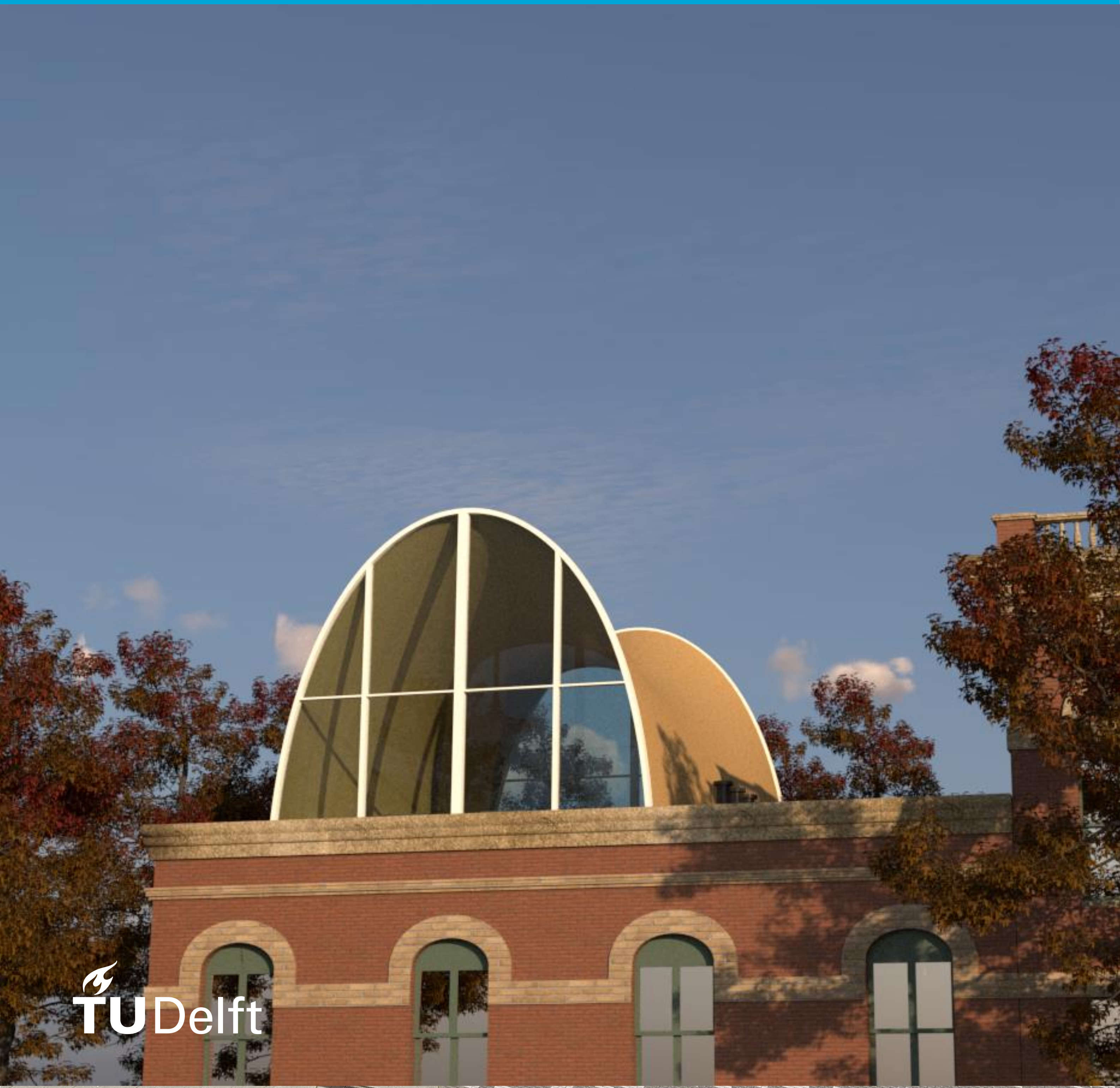

TU Delft

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Fjodor Serov

CTB3000-16 Bachelor Eind Project

BSc Civiele Techniek, Technische Universiteit Delft

5170176

fserov@tudelft.nl

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Supervisors: Ass. Prof. Dr. M.A. Popescu
Dr. ir. P.C.J. Hoogenboom

Abstract
In modern day structural engineering, the aim is to fulfil user requirements while minimizing their environmental impact. Among the promising innovations, material-efficient shell structures show potential, along with the exploration of earth as a construction material with contemporary technologies. However, the combination of these two elements remains an area requiring further investigation.

The primary objective of this study is to explore potential applications for earthen shell structures through a review of existing literature. Through a qualitative evaluation, the research sheds light on the distinctive characteristics and applications of stabilised and unstabilised earthen shell structures. It becomes evident that these two variants exhibit different characteristics and, consequently, offer potential for different practical applications.

Stabilised earthen shell structures, characterised by enhanced mechanical properties and durability, find relevance in applications where long-term structural integrity is important. On the other hand, unstabilised earthen shell structures exhibit advantageous features such as greater local availability, reduced environmental impact, improved hygroscopic properties, enhanced indoor comfort, and superior recyclability. These attributes position unstabilised earthen shell structures as potential candidates for employment in erosion-resistant climates or temporary construction scenarios.

While the findings illustrate the potential of unstabilised earthen shell structures in specific contexts, it is important to emphasise the need for further research in this field. more comprehensive exploration encompassing theoretical investigations, physical testing, and advanced modelling techniques. Through this comprehensive approach, earthen shell structures may emerge as a compelling outcome of the interplay between material-efficient construction techniques and sustainable materials.

Preface

During my study at the faculty of civil engineering at the TU Delft, my awareness in sustainable construction has been rising. In combination with my interest in modern architectural structures, surface structures were a subject that I wanted to dig deeper into. The fact that the evolution of nature and physics give a solution for geometries that minimise the amount of needed material for certain constructions, creating not only sustainable but also beautiful structures, I find simply fascinating. In my eyes, structural surfaces are a subject where mathematics, physics, architecture and even art can intertwine. It was an honour to explore the interplay of earthen construction and shell structures, potentially making such structures more accessible, specifically with the supervision of Ass. Prof. Dr. M. Popescu and Dr. Ir. P.C.J. Hoogenboom. I would really like to express my gratitude towards them, especially for the involvement, shared knowledge, and feedback on the process. Also, I would like to thank my friends Thomas Cramer, Joan Wiersma & Joep Wijnen for the support, discussions, and brainstorming sessions.

Fjodor Serov
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Contents

1. Introduction

In modern day structural engineering it is important to design structures that meet the requirements of the users while trying to minimise its climate footprint. This can be done by on one hand using materials more efficiently, while on the other hand using materials that minimise harmful and potential irreversible effects on the environment (Hussin et al., 2013). Currently, concrete is one of the most used construction materials worldwide. Yearly, 10 billion tonnes of concrete are being produced. For each tonne of cement produced, approximately 0.81 tonnes of CO_2 are released into the atmosphere, making the cement industry accountable for roughly 7% of global CO_2 emissions (Worrell et al. ,1999; Meyer, 2009). With the current growth of the population, it is important to evolve the construction industry into a more sustainable one (Van Bavel, 2013).

By constructing material efficient structures, the amount of needed material can be reduced. Since the 1910s structural surfaces have been designed to construct some of the lightest and most material-efficient structures (Bechthold, 2008). These structures are material-efficient because they derive their stiffness from geometry rather than from thickness (Tysmans et al., 2009). Figure 1 shows a concrete shell structure.

Figure 1 Concrete shell structure in Valencia, L'oceanographic. From *"Wikimedia Commons,"* by Chisloup, 2014 (https://web.archive.org/web/20161028145203/http://www.panoramio.com/photo/108391339). Licensed under CC BY 3.0

Meanwhile, the search for sustainable construction materials resulted in an increase in interest in earthen constructions. Worldwide, earthen constructions have been used since approximately 8000 BC. It is estimated that currently 30% of the world's population lives in earth-based dwellings (Minke, 2005). Due to beneficial economic and environmental properties, the number of published research articles about earthen construction has increased tenfold the last decades. (Costa et al., 2018; Pacheco-Torgal & Jalali, 2012).

As suggested above, shell structures and earthen construction both have potential to contribute to modern and sustainable construction methods. A question that rises is how the benefits of earthen construction could potentially be combined with the benefits of shell structures, for a synergetic effect**.** While there is an abundance of literature available for each subject individually, there is limited literature that explores the combination of both subjects. The goal of this paper is formulating an answer to the following question:

How can sustainable earthen shell structures be applied in practical contexts?

Based on existing literature, the objective of this research is to understand the current possibilities and limitations of earthen shell structures, trying to show the potential of a relatively sustainable material used in a material efficient structure. By analysing literature and linking characteristics of earthen construction and shell construction, potential applications can be formulated. If applications can be found, earthen shell structures could potentially have an actual impact on the construction industry.

The second chapter of this study will provide a brief review of available literature. In the first section of chapter two characteristics of concrete shell structures are elaborated. To understand the production of concrete and masonry shell structures, four shell structures, produced with contemporary methods, are analysed. The focus will be on their materialisation, structural properties, and fabrication methods. Two digital form-finding methods are elaborated briefly. The question driving this section is:

How are shell structures fabricated sustainably?

In the second section of chapter two, literature about earthen construction is explored. First, discussing the characteristics and properties of the material – showing what properties of earth fit the current standards of construction materials. Second, several ancient construction methods are examined. With the growing interest in earthen construction, various contemporary earthen structures are analysed in terms of their materialisation, structural properties, and fabrication methods. This analysis highlights innovations and techniques that promote the use of earth as a construction material as well as their physical properties. The central question guiding this section is:

How has earth been used in construction?

Based on the reviewed literature, the objective is to explore the possibilities and limitations of earthen shell structures. With the listed properties and characteristics of the material, as well as the fabrication methods of shell structures the goal is to find adequate applications.

The third chapter provides a detailed elaboration of the approach in determining these applications, by stating the method.

In the fourth chapter, the results of the performed analysis are presented. Based on the characteristics and properties of earth and shell structures the potential and limitations of earthen shell structures are clarified. By structuring the literature, general applications for earthen shell structures can be found. The result is supported with two conceptual designs of applications of earthen shell structures.
In the fifth chapter, the findings are discussed. Before the found applications can have an impact on the industry, more research is mandatory. In this chapter, identified weaknesses and potential enhancements of the research are presented. Also, suggestions and recommendations for further research are discussed.

To conclude the research, in chapter six, the findings and discussions are summarised to provide an understanding of the current possibilities and limitations of earthen shell structures. The conclusions drawn from this research aim to contribute to the potential of applying earthen shell structures in the construction industry, showcasing the potential of earth in material-efficient structures.

2. Literature

To understand the practical implementation of earthen shell structures, it is crucial to gain insights in the fabrication of shell structures. Additionally, understanding what earthen construction is and what properties of the material are relevant has significant value. Extensive literature is available on both subjects individually. Firstly, this section presents the state-of-the-art of shell structures. Secondly, earthen construction methods as well as earthen structures are reviewed. The examples elaborated in this chapter form a theoretical framework which is used for the results in chapter 4.

2.1 Sustainable shell structures

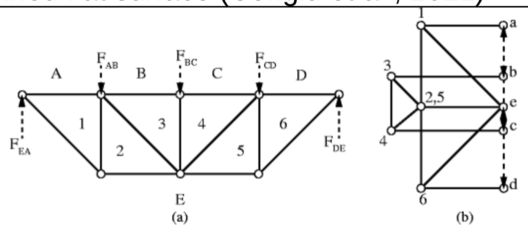
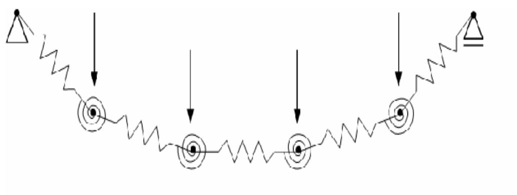
Eminent architects and structural engineers like Eduardo Torroja (1899 - 1961) and Félix Candela (1910 - 1997) are recognised for their contributions in the field of architecture, particularly for the designs of so called shell and folded plate structures. Using reinforced concrete Torroja designed the Algeciras Market Hall (see figure 2), a shell-structure with a thickness of only 10 cm spanning 48 m (Pablo, 2012). In 1958, for the Los Manantiales Restaurant in Xochimilco, Mexico City, Candela used hyperbolic paraboloid geometric forms in his structures (see figure 3). At that time, these forms were unexplored and hard to analyse precisely. Candela insisted on the unimportance of structural analysis when a designer chose a structurally appropriate form (Burger & Billington, 2006).

Figure 2 Algeciras Market Hall by Eduardo Torroja et al., From *"Wikimedia Commons,"* by Falcon Aumanni, 2010 (https://structurae.net/en/media/313430-algeciras-market-hall). Licensed under CC BY 2.5

Figure 3 Los Manantiales by Félix Candela et al. From *"Wikimedia Commons,"* by Yoshito Isono, 2001 (https://structurae.net/en/media/68363-xochimilco-restaurant). Licensed under CC BY 2.5

Currently, multiple digital form-finding tools are available for the design of complex formed and material efficient shell structures. Two examples are elaborated in table 1.

Table 1 *Examples of form-finding methodologies*

Thrust Network Analysis	*Particle-Spring system*
The Thrust Network Analysis (TNA) is a method for form-finding compression-only structural systems, which derive their stiffness form geometry, rather than from their thickness. Regardless of the material properties involved, TNA involves the simultaneous control of two reciprocal diagrams: the form diagram (Γ) and the force diagram (Γ*). An example of the two diagrams is shown in figure 4. According to Maxwell's principle, corresponding lines in these two diagrams must be parallel, ensuring equilibrium at each node by forming closed polygons in the other diagram. In the context of computational design, RhinoVAULT 2 for Rhinoceros, enables users to generate optimised compressed networks starting from a user-defined flat surface (Congiu et al., 2021).	The Particle-Spring System method is an iterative dynamic equilibrium method for determining static equilibrium solutions for shell structures. From certain boundary conditions a network of springs with internal forces are generated, resulting in elongation. The elastic strains of the springs will induce reacting forces to other springs, until the internal forced will reach a state of equilibrium. There are two kinds of simulations, the hanging cloth simulation, for compression-only structures, and the stretch cloth simulation, for anticlastic geometries. Kangaroo, a plugin for Rhinoceros, allows users to model such shell structures (Congiu et al., 2021). A visualisation of the Particle-Spring System is shown in figure 5.
 **Figure 4** Maxwell's reciprocal diagrams, (a) form diagram, (b) force diagram. From *"Maxwell's reciprocal diagrams and discrete Michell frames"* by (Baker et al., 2013)	 **Figure 5** Particle-spring method. From *"Particle-spring method for form finding grid shell structures consisting of flexible members"* (Kuijvenhoven & Hoogenboom, 2012)

A disadvantage associated with constructing concrete shells is that a complex shaped and custom formwork is required. Typically, a disposable formwork from timber or foam is used, as shown in figure 6, leads to significant material waste and high costs (Popescu et al., 2018a).
However, research indicates that fabric formworks effectively address these disadvantages when building concrete shell structures. For instance, Veenendaal & Block utilised a cable-net reinforced textile to fabricate a structure, resembling the hyperbolic paraboloids Candela used (2014). Another successful example involves a knitted textile stay-in-place formwork, which was tested by designing a small-scale footbridge prototype (Popescu et al., 2018b). Studies suggest that shell structures utilising

Figure 6 Falsework of the shell of the Chapel Lomas de Cuernavaca, Mexico, 1959, by Félix Candela et al. From *"Design process for prototype concrete shells using a hybrid cable-net and fabric formwork"* (Veenendaal & Block, 2014)

reusable textile formwork combined with reinforced shotcrete can be an economical alternative for traditional linear elements (Cauberg et al., 2012). These examples demonstrate that using fabric formworks and concrete offer potential of construction of material-efficient structures. Some relevant shell structures will be reviewed below, focussing on their materialisation, structural properties, and fabrication methods.

Concrete shell with hybrid cable-net and fabric formwork

Some of the thinnest known shell structures are hypars, but with slight changes of their geometries, their structural behaviour can be improved. The goal of this conceptual design was to minimise the maximum deflection. A timber frame was used to tension a cable net from 2 mm stainless steel cable. On top of the cable net a fabric was applied with a tensile strength of 54-60 kN/m. The concrete that is used for the shell structure consisted of the following mixture:

- 1 kg cement
- 0.1 kg microsilica
- 0.7 kg sand aggregate
- 0.015 kg PVA fibres
- 0.24 L water
- 0.010 – 0.015 L plasticiser
- 0.015 kg stabiliser

Figure 7 Concrete shell with hybrid cable-net and fabric formwork by D. Veenendaal and P. Block. From *"Design process for prototype concrete shells using a hybrid cable-net and fabric formwork,"* (Veenendaal & Block, 2014)

A part of the wooden frame was removed resulting in the final structure resting on the two lower points of the hypar-geometry (Veenendaal & Block, 2014). The structure is shown in Figure 7.

Concrete shell bridge with knitted fabric formwork

In 2018 M. Popescu et al. explored a prototype of a concrete shell bridge. The construction method uses knitted technical textile with integrated reinforcement as a formwork. This method can be used for constructing material saving, labour reducing and cost-effective concrete structures. This construction method has several benefits when compared to traditional methods. This bridge, shown in figure 8, is lightweight, easy to manufacture, the materials are highly transportable and quick to assemble (Popescu et al., 2018).

Figure 8 Concrete shell bridge with knitted formwork by M. Popescu et al. From *"Building in Concrete with an Ultra-lightweight Knitted Stay-in-place Formwork: Prototype of a Concrete Shell Bridge"* (M. Popescu et al., 2014)

Materials

The structure consists of the following components (Popescu et al., 2018):

- Timber edge supports
- Thread rod ties

- 3D knitted textile
- Bending-active rod
- Tensioning ribbons
- Cement-paste coating
- Mortar
- Reinforced structural concrete

Structure

The stiffness of the structure is gained by geometric stiffness due to its form, structural corrugations due to the tie ribbons and bending-active rods and steel tie rods that connect the abutments of the bridge. The structure uses bending active rods and tensioning ribbons to span the 3D knitted textile in the desired form. On top of this textile a layer of high strength cement-paste coating is applied, light enough not to load the structure excessively, strong enough to support the layer of concrete (Popescu et al., 2018).

Fabrication

The fabrication process of this structure can be divided in three parts (Popescu et al., 2018):

1. <u>Fabrication of the knitted textile</u>
   For the fabrication of the knitted textile for the specific shape a knitting pattern is required. Using specific software, the desired 3D geometry is converted to a 2D knitting pattern. A knitting machine reads the pattern and produces the textile. The final textile not only depends on the used knitting pattern, but also on different properties of the knitting machine and the yarn used for the textile.
2. <u>Tensioning</u>
   For this structure the textile was tensioned between nine rods. First, the textile was strung on the rods and fixed with rubber profiles. Next, the rods were tensioned into the desired shape.
3. <u>Applying the layered concrete</u>
   Before applying concrete, a thin layer of high-strength cement was applied to the textile. Using final-element-analysis the stresses in material were calculated. The conclusion was that a minimum of 4 mm had to be applied. This layer consists of 1.5 mm of high-strength cement paste and 4 mm of mortar reinforced with epoxy coated carbon fibre reinforcement mesh.
   After curing a layer of concrete was applied of approximately 5 – 10 cm, depending on the slope of the of the plane.

<u>Unreinforced Timbrel Vault with cardboard formwork</u>

In 2012 M. Rippman et al. presented the earlier mentioned plugin RhinoVAULT. This tool is used to form-find funicular structures. An approximately 30 m^2 prototype of the founded form, based on this design process, has been built at the campus of ETH Zurich in 2011. The structure is shown in figure 9.

Figure 9 Timbrel Vaulting Using Cardboard Formwork by M. Rippman et al. From "*No Tech magazine"* (De Decker, 2011)

Material

The material used for this vaulted structure is thin brick-tiles and mortar (Rippman et al., 2012).

Structure

The compression only structure is constructed without reinforcements. The computational software provided the designers with a form and force diagram, informing them with graphical information. This allowed them to put more material only where it was locally needed and optimise its topology (Rippman et al., 2012).

Fabrication

The tiles were laid on top of a cardboard formwork, fabricated computationally. The formwork is assembled onsite and is inexpensive and potentially recyclable. To reduce the amount of used cardboard, the cardboard was stacked on top pallets.

One of the challenges of using cardboard formworks is removing the formwork from the surface of the shell structure. The formwork should be removed simultaneously and evenly, otherwise asymmetrical loads can cause failure. To achieve this, cardboard spacers were applied under the formwork. By saturating the spacers with water, the whole framework was lowered due to the weight of the pallets (De Decker, 2011).

<u>*NEST HiLo, Dübendorf, Switzerland*</u>

The NEST HiLo shell is a material efficient concrete roofing system of a duplex penthouse apartment. The penthouse is 16 x 9 m in area and has very strict energy performance. The roof functions as a solar collector as well (Block et al., 2017). A picture of the structure is shown in figure 10.

Figure 10 NEST HiLO by P. Block et al. From "*Architecture and Building Systems"* (Architecture and Building systems, 2021)

Material

For the reduction of thermal bridging, the shell structure is constructed as sandwich composite, ferrocement reinforced, concrete faces. Ferrocement is chosen for improved thermal conductivity of the roof. Between the two layers of high strength C90/C105 concrete (shotcrete) a polyurethane core is found for isolation. The shell structure is fabricated using a prestressed cable-net and fabric formwork system. The shell thickness varies between 3 and 30 cm, with an average thickness of 8 cm. The sandwich design increases the complexity in terms of creep and shrinkage. Addressing this issue, the middle of the shell is only one level of concrete (Block et al., 2017).

Structure

The construction of the anticlastic shape is made possible using a flexible formwork, allowing for the realization of complex curved surfaces. The shape of the structure is optimised making it more material-efficient than traditional analytical forms like the hyperbolic paraboloid.

Unlike conventional structures, the shell does not incorporate edge beams. Instead, it features thin edges that gradually thicken towards the five support points. The span of the shell typically ranges from 6 to 9 meters. It is supported on five support-points, with free edges along its entire perimeter. The structure weighs 29 metric tonnes (Block et al., 2017).

Fabrication

The geometry of the structure was obtained using the force density form-finding method. Earlier hypar structures have been known to exhibit significant deflections. For this structure, a method considering the load of fresh concrete was used to gain the optimised geometry as a result. The forces in cable-net were carefully adjusted to ensure that under given loads of the wet concrete, the resulting concrete shell takes the form of the target shape. Using a prestressed cable-net formwork with fabric shuttering, makes the formwork lightweight and easily transportable (Block et al., 2017).

2.2 Earthen construction

Earthen constructions have been used worldwide for millennia. Through the time there have been various building techniques. To understand how earth can be applied in construction, an understanding of its properties and fabrication methods are required. In this section, the characteristics and properties of the materials are listed. Consequently, (traditional) building methodologies will be elaborated. Finally, contemporary earthen structures and fabrication methods are analysed.

Local availability

The local availability of earth as a construction material is a significant factor in sustainable building practices. Numerous examples demonstrate the utilization of locally available materials, with some projects even utilizing earth excavated on-site (Heringer et al., 2019)**.** The use of locally available materials offers several advantages, one of which is the reduction in the need for transportation. By sourcing materials from the immediate surroundings, the embodied energy associated with transportation is minimised (Marsh et al., 2020; Pacheco-Torgal & Jalali, 2012; Reddy & Jagadish, 2003). This approach is not limited to specific regions but has been implemented in various countries and climates worldwide (Zami & Lee, 2010).

Costs

The costs of earthen construction in the UK consist mainly of labour costs (Zami, 2021). In more developing countries the costs of earthen construction consist mainly of the cost of (transportation of) stabilisation materials (Zami & Lee, 2010b). With modern technologies contributing to the decrease of labour and the use of raw natural and local stabilised construction these costs could potentially be decreased (De Ávila et al., 2021).

Hygrothermal & hygroscopic properties

Earth is known to have favourable hygrothermal properties. Research shows that bricks made from various mixes have similar hygroscopic/hygrothermal properties. The hygrothermal performance of a wall is also dependent on the thickness (Giada et al., 2019).

The combination of high thermal effusivity, high density, high heat capacity and limited thermal conductivity increases likelihood of saving energy and increasing comfort (Cagnon et al., 2014).

Also, the quick moisture regulation of earth increases indoor comfort. According to various literature the Moisture Buffer Value for unstabilised rammed earth is between 1 and 3.7 g/m^2 x % which are considered good and excellent values (De Ávila et al., 2021). However, stabilising the earth will reduce the favourable performance (Arrigoni et al., 2017).

Acoustic properties

Acoustic insulation is measured with the Sound Reduction Index R (db), which is an index that shows the ratio between the acoustic power incoming on an object and the acoustic power exiting the object. This value depends on the thickness of the object. Earlier research shows that sound passing through a 300 mm rammed earth wall loses 57 dB of sound energy (De Ávila et al., 2021).

Environmental benefits

Wide variety of soils can be used for rammed earth without significant industrial manipulation. The preparation, transport, and handling of loam on site requires only ca. 1% of the energy needed for the production, transport and handling of baked bricks or reinforced concrete. Loam produces virtually no environmental pollution and has relatively low CO_2 emmisions (De Ávila et al., 2021; Minke, 2005). Stabilising the earth will increase the embodied energy, but the material still can be favourable compared to other materials (Reddy & Jagadish, 2003b).

Raw earth can be recycled an indefinite number of times over an extremely long period. Old dry raw earth can be reused after soaking in water, so raw earth never becomes a waste material that harms the environment. However, recycling cement stabilised earth decreases its strength (Bruno et al., 2020).

Vulnerable for erosion

Form literature it becomes clear that erosion is a relevant aspect to take into account when building with rammed earth. Researchers analysed a stabilised rammed earth wall with 5% natural lime. The result after 20 years of weathering (+- 1000 mm/year) was that 2mm (0.5% of wall thickness) had eroded. A raw rammed earth wall had lost a mean thickness of 6.4 mm corresponding to 1.6% of wall thickness. This means that rammed earth surfaces may need maintenance during its service time (Bui et al., 2009).

Cob

According to Niroumand et al. cob is one of the simplest building techniques (2013). For this building technique no formwork or internal structure is needed, as the used material is being piled and moulded into shape to create walls. The shaping is usually done by hand or trowel. To create Cob often a mix of sand (or other aggregate), clay and water is used in combination with fresh straws for extra stiffness (Niroumand et al., 2013).

Figure 10 Taos Pueblo, New Mexico. From *"Wikimedia Commons"* by J. M. Burke, 2017 (https://commons.wikimedia.org/wiki/File:Taos_Pueblo_2017-05-05.jpg). Licensed under CC BY 4.0

Cob has been used worldwide for centuries. In different cultures the technique is applied in a slightly different way. In Ireland and the United Kingdom cob has been used for rural farmer houses to luxury estates, at least since the 16th century. In Yemen, for example, where the cob-technique is named *zabour*, multi-story constructions have been constructed since the thirteenth century. English colonists have spread cob to Australia, North America, and New Zealand. Another example is the still thriving village of Taos Pueblo in New Mexico. The village, dating from the 11th century and shown in figure 11, has multi-story dwellings and is the oldest continuously occupied village in North America (Niroumand et al., 2013).

Adobe bricks

Adobe bricks are earthen naturally dried bricks baked in the sun. To dry the bricks at least one week of rainless weather is needed (Niroumand et al., 2013). For the bricks a mixture of sand, clay, silt, and water is shaped in a mould. Sometimes the bricks are stabilised with natural fibres like straw, asphalt emulsion, lime, or Portland cement. In the past, vernacular builders used manure, straw, blood, or plant juices (Costa et al., 2018). The amount of energy needed for production is relatively low.

Figure 11 Shibam buildings, Yemen. From *"Wikimedia Commons"* by M. Gropa, 2017 (https://commons.wikimedia.org/wiki/File:Old_Walled_City_of_Shibam-109044.jpg). Licensed under CC BY 3.0

Adobe bricks have been used at least since the Roman Empire for constructing Republican domus (Quagliarini et al., 2010). In Yemen, the world's first skyscrapers were built in the seventeenth century. The structures are shown in figure 11. Adobe bricks are known to have relatively great fire resistance and low sound-transmission levels. A disadvantage of adobe bricks is that the ratio between gross floor area and lettable floor space is unfavourable (Niroumand et al., 2013). Using adobe bricks excessive shrinking of the earthen material can be avoided. Adobe bricks are often very suitable for funicular structures. If the material is treated properly, it can last for hundreds of years and afterwards it can be recycled completely. This recently has caused a rise in interest in the material (Calabria et al., 2009).

Wattle and daub

Wattle and daub is an ancient technique where reeds, bamboo, branches and similar twigs are woven into a structure on which daub (or mud) is applied (Shaffer, 1993). The technique has been used since the neolithic age all over the world. Due to the irregularities of the woven structure the daub adheres quite well. Often the daub is smeared on the wattle by hand. Due to the flexibility of the woven matrix structures made with this construction method are performing relatively good in seismic regions (Niroumand et al., 2013).

Figure 12 METI School exterior in Bangladesh. From *"Wikimedia Commons"* by Tschaperkotter, 2018 (https://commons.wikimedia.org/wiki/File:Meti_School_Exterior.jpg). Licensed under CC BY 4.0

This method can also be applied in contemporary architecture. In 2004 architect A. Heringer applied this method for the METI school in Bangladesh, shown in figure 12. According to Heringer, local workers, that could not read a metric ruler or had never used a level, successfully built a beautiful school using mostly local materials, showcasing that not many tools are needed for this construction method (Heringer et al., 2019). This project demonstrates great potential for wattle and daub in modern day structural engineering for hard-to-reach areas.

Rammed Earth

Rammed earth is a technique where soil is compacted into a relatively high-performance structural material (Walker, 2010). In the construction industry the technique of ramming earth has had a significant influence in various cultures. For example, rammed earth has been used parts of the great wall of China or in the kasbahs in Morocco (see figure 13). In fact, China has evidence of some of the oldest rammed earth structures dating from the Neolithic period (Niroumand et al., 2013). For more than thousands of years builders produce rock-hard structure making use of simple tools for soil compaction. Usually, a mixture of sand, gravel, soil, and water is being compacted in layers between formworks (Costa et al., 2018). Research concludes that reduction of water content in the mix, the strength increases. Despite decreasing its environmental impacts, stabilisers like cement or lime can be added to decrease the amount of erosion and increase the compressive strength (Heringer et al., 2019; Jaquin et al., 2009).

Figure 13 Aït Ben Haddou, Morocco. From *"Wikimedia Commons"* by Kris.buelens, 2013 (https://commons.wikimedia.org/wiki/File:MA2013_2348.jpg). Licensed under CC BY 4.0

The fluctuating interest in earthen construction

As presented above, various methods have been used for constructing buildings using earthen materials. Despite the presence of favourable properties of the material, in some regions the popularity of the use of the material has been declined. Literature mentions the following interconnected reasons:

- One of the reasons the use of earth decayed is the fact that the industrial revolution made mass-produced materials cheaper and more accessible. Before industrialisation it was hard to transport materials from further away. Most buildings had to be built with locally available materials like for example wood and earth. Ramming earth for example was a labour intensive, low technology process (Gangarao et al., 2020, Treloar et al., 2001).
- Due to industrialisation and the emergence of rail roads, materials like concrete, steel and bricks gained popularity. In these industrialised countries these materials became a symbol of what modern construction should be (McHenry, 1984).
- In most countries colonised by Europeans, all layers of the hierarchy used earth as construction material. The main differences between buildings for the rich and the poor were expressed in size and ornamentation. Around the 1800s, when European colonisers began to see earthen construction as something foreign, archaic, and even primitive, they started to export not only industrial materials like fired bricks, but also their building culture, including their (material) hierarchies and technologies. This spread the (negative) European view on earthen construction to these countries as well (Heringer et al., 2019).

While in almost the whole 20th century interest declined, in the 1930s and 1940s the material gained interest due to investments of some oil companies. After that, earth was only for the rich, building in luxury real-estate in Spanish Colonial styles or for the poor, that had to construct for themselves with their own hands. Almost a whole generation of engineers, architects, and contractors did not work with earth, losing experience in building earthen constructions.

However, the last three decades, the interest has been increasing. One reason is the low-cost of the material (Zami & Lee, 2010b). Another reason is that in modern day structural engineering it has become more and more important to build sustainable structures (Niroumand et al., 2013). Gomaa et al. mentions that there are earthen constructions built using modern technologies, creating balance between human labour and machines, decreasing the production time (2022). Especially innovations for building with rammed earth show potential. Multiple companies and research institutions acknowledge the sustainability of the material and try to implement it to build structures that meet the current standards.

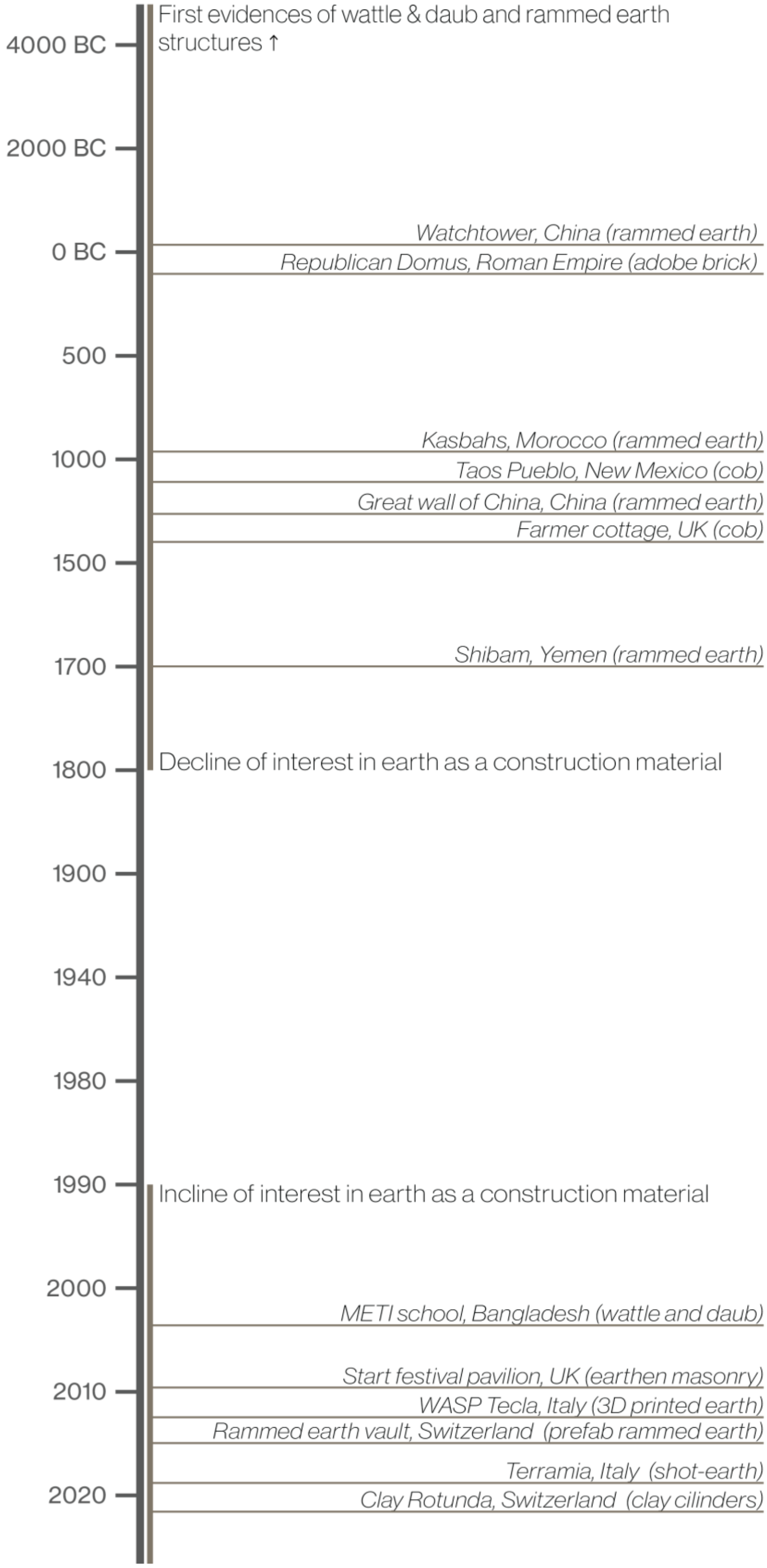


Figure 14 Timeline of fluctuating interest in earthen construction

For instance, A. Curto et al. explores a relatively sustainable construction material named “shot-earth”. This technology is based on high-pressure spraying of (stabilised) soil mixed with aggregates and water (2020). This soil compacting method is very comparable to the environmental impact and structural working principle of rammed earth, which is recognised as a relatively sustainable construction material (walker, 2010; Kariyawasam & Jayasinghe, 2016, Curto et al., 2020). The research of A. Curto et al. concludes that the mechanical properties of shot-earth can be similar to that of a low strength concrete (2020). A timeline of the fluctuating interest is shown in figure 14. A variety of contemporary building techniques using earth are listed in this section below.

Ricola Krauterzentrum, Laufen, Switzerland

In 2013 Lehm Ton Erde GmbH and Herzog & de Meuron Architects constructed the Ricola Krauterzentrum (see figure 15). This industrial building, located in Laufen in Switzerland, is one of the most well-known examples using prefabricated earthen elements on a large scale. The building covers 1240 m^2 and is made of 1130 tonnes of rammed earth. This project is relevant because it shows how a building can be constructed using prefabricated earth (Heringer et al., 2019).

Figure 15 Ricola Krauterzentrum, Laufen, Switzerland. From *"Wikimedia Commons"* by Keimzelle, 2017 (https://commons.wikimedia.org/wiki/File:Kraeuterzentrum_Ricola_2.jpg). Licensed under CC BY 4.0

Structure

The structure consists of non-load-bearing prefabricated rammed earth elements that carry their own weight. The earthen walls aren't part of the primary structural system. Other comparable structures, for example the Rauch Haus, is a load bearing structure constructed in-situ (Heringer et al., 2019).

Fabrication

The rammed earth wall elements were fabricated in a warehouse nearby the building site. Lehm Ton Erde developed a ramming machine which allowed the elements to be mass-produced. This mass-production happened at strict Swiss standards for structural capacity and material consistency. The ramming machine was conceived in six months, ramming the 670 elements took eight months. The earlier mentioned Rauch Haus, which is a smaller project, took more than a year to construct (Heringer et al., 2019).

Material

The Ricola Krauterzentrum is materialised as economic and sustainable as possible. The earth for the project was excavated from the site itself. For extra strength further stone materials from the surroundings (radius of 8 km) were added. The use of (polluting) cement was minimised, so volcanic tuff and lime was used for stabilisation (Marsh et al., 2020b). Before choosing rammed earth as the construction material, Herzog & de Meuron experienced difficulties with other materials. Timber could not be used due to hygienic reasons; the environmental impact of steel was unfavourable and limestone bricks were too expensive. The building seems to have great hygrothermal regulations for the plant storage (Heringer et al., 2019).

OMICRON Monolith, Klaus, Austria

For the OMICRON headquarters in Austria, Anna Heringer and Martin Rauch were asked to design a place for contemplative retreat inside an atrium of the office building. The duo designed a two story, free form shaped monolithic womb-like structure. This project is inspired by the project Heringer and Rauch did before in Bangladesh and Zimbabwe (Heringer et al., 2019). The indoor structure is shown in figure 16.

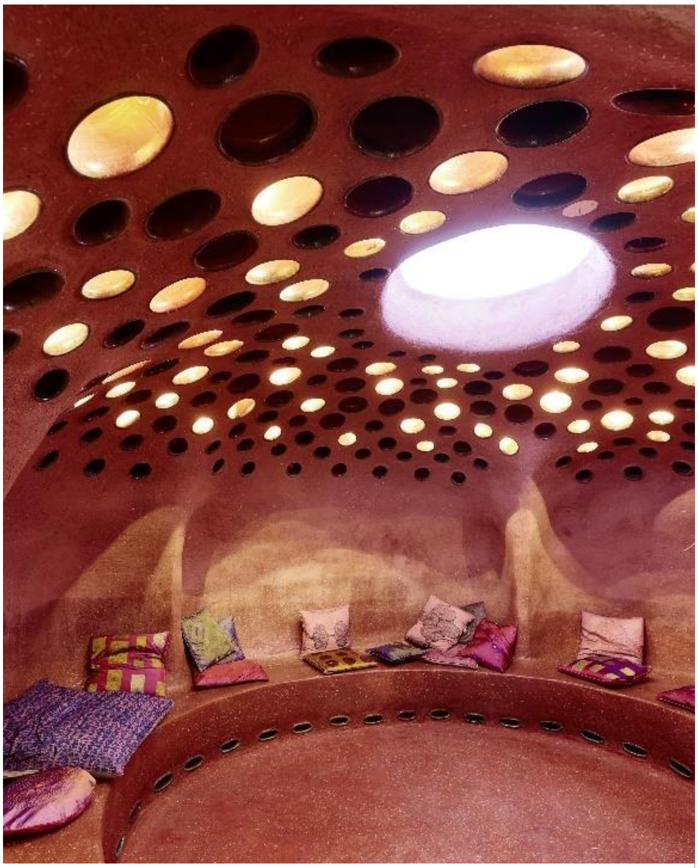


Figure 16 OMICRON Monolith, Klaus, Austria. From *"klomfar.com"* by Bruno Klomfar, 2016 (http://netzwerklehm.at/lehmbau/omicron-crossing-border)

Material

The materials used in this construction were mud, mixed with a small amount of stones and natural fibres. Geotextile webbing was used as horizontal reinforcement. A metal ring was added, increasing the tensile strength and bearing the load of the inner dome. Hollow ceramic pots were placed in the clay structure for extra strength and stability. For extra acoustic insulation, a rough finish of clay plastering with cork was applied. The hygroscopic properties of earth allowed the Monolith to breathe and create a perfect moisture-vapor balance (Heringer et al., 2019).

Structure

As the monolithic structure needed to be lightweight, reducing thickness of importance. As the structure is stiffened with ribs, the form resembles with the form of a bell pepper. The earthen structure with a thickness of 15 cm was reinforced with geotextile and a metal ring, increasing the tensile strength. Unique in this structure is the application of hollow ceramic vessels, which stiffens the earthen mixture, while decreasing the weight. These hollow spaces also acted as acoustic insulation and contained lighting elements. As the structure was inside, externalities like weathering aren't taken in consideration (Heringer et al., 2019).

Fabrication

The OMICRON monolith was fabricated using the zabour method. In this method, without using formwork, the structure is formed completely by hand, making it comparable to pottery. "*Reflecting on this project actually provokes me in retrospect, because from an economic and common-sense perspective building this way should be inexpensive. The material is so widely available and so low-cost, it only requires human labour to shape, and this results in job creation. But in countries like Austria, it would have actually been cheaper to 3D-print our design with a cement-based material or plastic polymers. Something is fundamentally amiss with our socioeconomic system if this is the case. A system that does not consider the negative impact of a material, and therefore the true cost of construction—one which taxes human labour but not carbon emissions or machines—is simply not sustainable*", Anna Heringer reflects (Heringer et al., 2019).

WASP Tecla, Massa Lombarda, Italy

Since 2012 WASP (World's Advanced Saving Project) has been developing a construction method focussing on digital fabrication and circularity. Their goal is now to construct sustainable earthen housing with a high performance for living, making use of 3D printing technologies (Moretti, 2023). The housing project is shown in figure 17.

Figure 17 WASP Tecla, Massa Lombarda, Italy. From *"3Dwasp.com"* by WASP, 2021 (https://www.3dwasp.com/en/3d-printed-house-tecla/)

Material

WASP uses raw earth, that is found as locally as possible. Starting with the analysis of the local soil, it is possible to design an appropriate mixture for the required structural performance, in this case looking at strength and printability. Raw earth is a mixture of clay, sands and pebbles (maximum size of 8 mm). After filtering the found soil, it is mandatory to (locally) find a natural fibre like for example rice straw, wheat straw, coconut or banana. The fibres have to be prepared to be mixed with the clay and aggregate to create a building material that meets the requirements. Often a printable building material can be produced that is based on local raw material for 95%. Adding water to the dry soil and mixing it with a muller results in consistent and properly kneaded mixture (Moretti, 2023).

Structure

When designing a 3D-printed structure it is relatively easy to optimise its topology by placing more materials in places where the performance of the structure should be higher. This is mandatory, as the (locally found) earthen mixture does not have the same characteristics as advanced concrete materials (Moretti, 2023).

Fabrication

Starting with the analysis of the local soil, it is possible to design an appropriate mixture for the required structural performance, in this case looking at strength and printability. After completing the mixture, the material is pumped to an extruder and printed with constant flow and pressure regulation using sensors (Moretti, 2023).

Clay Rotunda, Bern, Switzerland

The Clay Rotunda is the outer, soundproof shell of a high-fidelity music auditorium built inside the Gurten Brewery in Bern. The shell protects the music hall from external noises. “Quieter than the most secluded Swiss mountain valley covered metres deep in snow”, says Jürgen Strauss, specialist in sound engineering (Straus Elektroakustik, n.d.). Using computational design, a cylindrical structure is designed with a diameter of almost 11 meters and a height of 5 meters. The building, shown in figure 18, is a completely zero-waste and zero-emissions construction (Parametric Architecture, 2023).

Figure 18 Clay Rotunda, Bern Switzerland. From *“Archdaily.com”* by Gramazio Kohler Research, ETH Zurich, 2021 (https://www.archdaily.com/964980/clay-rotunda-gramazio-kohler-research)

Material

The structure is made from zero-waste and fully recyclable material. The material consists of local swiss 40% clay, 45% sand, 15% small stones. Afterwards 1/16 water is added. This mix was then formed into 31183 clay cylinders with a height of 15 cm and a diameter of 9 cm. As the structure was inside, externalities like weathering weren’t taken in consideration (Baudokumentation.ch, n.d.).

Structure

The slender structure has a cylindrical form with diameter of 11 meters, a height of 5 meters and a thickness of 15 cm. The construction retrieves its stability from the undulated design. This also increases its ability to withstand buckling effects (Parametric Architecture, 2023).

Fabrication

The construction was fabricated in 50 days. First, a computational model was created. This model calculated the position of each of the 31183 clay cylinders, considering the properties of the clay, including shrinkage (Baudokumentation.ch, n.d.). Also, the limitations of the robotic arm, which was used to place the cylinders into position, were integrated in the design of the model. When the robot had placed the cylinders into position it compressed the cylinders with 60% of the original height to assure a strong and interlocking aggregation (Parametric Architecture, 2023).

Start Festival Earth Pavilion, London, UK

In 2010 the Prince of Wales initiated a sustainability themed garden party in London. Peter Rich Architects and vault designer Michael Ramage designed a temporary pavilion showcasing a sustainable shell structure constructed using locally available materials wherever possible (Jovanovic et al., 2018). The structure, shown in figure 19, covers 75 m^2 with approximately 40 m^2 of usable surface (Dahmen & Ochsendorfs, 2012). This project is relevant because it shows how a shell structure using earthen masonry can be sustainable option for constructions.

Figure 19 Start Festival Earth Pavilion by Peter Rich Architects and Michael Ramage, London, UK. From *"light-earth.com"* by Light Earth Designs LLP, 2010 (http://light-earth.com/portfolio-item/the-earth-pavilion/)

Material

The goal of the project was to minimise the use of cement to create a sustainable form of construction using locally available materials, wherever possible. The shell of the pavilion is built using two layers 20 mm thick cement stabilised earth tiles, with a geotextile in between. The tiles consisted of nine parts of locally sourced clay-rich soil, one part of Portland cement and a small amount of locally available sand. The total assembly was 60 mm thick (Dahmen & Ochsendorfs, 2012).

Structure

The complex-formed structure putted newly available computational software for structures into practise. This software is based on graphic statics and 3-D Thrust Network Analysis.
The structure itself was reinforced using geotextile grid. This increased the capacity of tensile stresses that can arise when the thrust line exits the body of the structure, for example when asymmetrical wind loads occur. However, the compression strength of the material was 50 times greater than the maximal occurring compressive stress (Jovanovic et al., 2018).

Fabrication

To create a complex formed shell structure, often a formwork is used. The inner layer of this shell structure was constructed on a plywood frame that was pre-cut using computer numerical control machines. The costs and the reusability of this formwork is unclear. Fast-acting gypsum cemented the earthen tiles of the inner layers. On top of this layer an interstitial geotextile grid was applied, embedded in cementitious mortar. The last step was to apply the external skin, also made from earthen tiles (Dahmen & Ochsendorfs, 2012).

Terramia, Milan, Italy

iIn 2019 MuDD architects constructed three prototypes of economical biobased housing for the Milan Design Week. These prototypes showcase on how this construction method could be applied for sturdier versions of tents or humanitarian shelters (Reed, 2019). The goal of the project was to highlight that quality housing can be made with this relatively cheap and fast construction method (Chaltiel & Veenendaal, z.d.). The humanitarian shelters are shown in figure 20.

Figure 20 Terramia Humanitarian Shelter, Milan, Italy. From *"akt-uk.com"* by NAAR0, 2019 (https://www.akt-uk.com/projects/terramia/)

Material

The materials used for the Terramia are a mix of clay with hard sand and fibres, local bamboo, and jute fabric (Chaltiel & Veenendaal, n.d.).

Structure

The structure uses fabric formworks to achieve the desired compression only form. The bamboo keeps the fabric in tension. On top of this fabric a shot-earth layer is sprayed to create a hardened surface (Reed, 2019). However, only a thin layer of earth is applied to the structure, causing the structure to appear relatively fragile.

Fabrication

This fabrication methods combines ancient materials in combination with high-tech tools. Using these high-tech tools three domes were created in a time span of five days, without requiring skilled labour. First, the bamboo is raised to create a skeleton. Next, the fabric is spanned creating a shell-surface. This fabric is tailor-made, reducing the total costs of the production. Then, a layer of shot-earth is sprayed on top using drone-technology. The nozzle of the spray is attached to the drone. This way, the wet mix can reach the whole structure. Using the same technique, dry fibres were sprayed for insulation (Reed, 2019).

Prefab rammed earth vault, Zürich, Switzerland

In 2014 Martin Rauch led a team of twenty-six students on a practical research project to earthen vaulted structure. After discussing several alternatives, the final design was defined by six wide arches and six domes that open outwards. The cupola, shown in figure 21, now serves as an inspiration for further innovative and sustainable projects (Loam Cupola rises on Zurich's ETH campus, 2010).

Figure 21 Prefab rammed earth vault, Zürich, Switzerland. From *"Block Research group"* by Gian Salis, 2014 (https://block.arch.ethz.ch/brg/teaching/rammed-earth-vault)

Material

The vaulted structure consists of 19 pneumatically rammed earth elements. The loam was locally sourced. A metal plate was used to protect the structure from water. Rammed earth without stabilisers is known to be vulnerable for erosion (Narloch et al., 2015).

Structure

The structure consists of arches in multiple directions. This was the first time that such a vaulted structure was made from prefabricated rammed earth elements. The experiment showed that the compressive strength is independent of the direction in which the rammed earth layers run (Loam Cupola rises on Zurich's ETH campus, 2010).

Fabrication

During a 14-day workshop students fabricated the rammed earth elements in a prefabrication hall. Robust wood formworks were filled with layers of local loam. This loam has been compressed with pneumatic rammers. The elements, weighing up to three tonnes, were placed onto the foundation using a pneumatic crane. To finish the construction, students plastered the joints and filled the holes. A metal waterproof roofing plate was placed on top (Loam Cupola rises on Zurich's ETH campus, 2010).

3. Methods & materials

In the preceding chapter, a review of the relevant literature was conducted to explore the characteristics of both shell structures (see section 2.1) and earthen construction (see section 2.2). The primary objective of this research is to address the central question: “How can sustainable earthen shell structures be effectively applied in practical contexts?” To achieve this, an analysis of the reviewed literature is performed.

The analysis begins with a qualitative assessment of the characteristics of earthen materials, distinction between stabilised and unstabilised variants is made. Identifying relationships between these characteristics allows to classify them accordingly. To provide a benchmark for comparison, the characteristics of concrete are considered as a reference point. In this analysis only cement as stabilisation material is considered.

Furthermore, various construction methods for shell structures have been reviewed. By comparing these methods with those utilised in earthen construction, we seek to identify commonalities and matching characteristics. This comparative analysis serves as a crucial step in establishing the groundwork for formulating applications of earthen materials in shells structures.

Once the construction methods are identified, the subsequent step involves formulating applications by making a choice between utilizing stabilised or unstabilised earth. To ensure that the applications align and benefit from the choice of material, the decision-making process is based on the characteristics identified earlier.

To ensure that the found applications are meaningful in a more practical context, the evaluation is supported by the presentation of two more detailed conceptual examples of potential applications, illustrating the potential advantages of incorporating earth as a construction material.

By combining the insights gained from the analysis of earthen characteristics, construction methods, and potential applications, the way can be paved for the realization of sustainable and material-efficient earthen shell structures in practice.

4. Results

This chapter presents the results of a literature analysis focused on the use of earth as a construction material for sustainable shell structures. The first section elaborates the differences between stabilised and unstabilised earth, offering an overview of their distinct properties and characteristics. The subsequent part focuses on the elaboration of fabrication methods for earth-based shell structures, with a specific emphasis on the utilisation of fabric formworks. Finally, the third section presents practical applications of earth-based shell structures, supported by two elaborated examples.

4.1 Materialisation of earthen shell structures

The properties and characteristics of earth as a construction material, reviewed in chapter two, are summarised in figure 21. In the figure the properties were qualitatively evaluated based on their suitability for constructing sustainable shell structures. Upon structuring and grouping these properties, a distinct difference between raw earth and stabilised earth became apparent. Figure 22 visually represents this distinction. These figures, situated on the next page, include the relevant references for this chapter.

The properties and characteristics of earth can be regrouped into three groups: structural characteristics, characteristics of comfort and environmental characteristics.
The structural characteristics encompass the mechanical properties (e.g. strength) and durability, which directly influence the design of shell structures. In this category, stabilised earth demonstrates a relatively higher score compared to raw earth. These properties have direct effect on the design of shell structure. In this category, stabilised earth has relatively great score, in comparison to raw earth.

On the other hand, characteristics of comfort, including acoustics, hygroscopic and hygrothermal characteristics, are indicators of the comfort for the users provided by the structure. Here, raw earth scores relatively high, if compared to stabilised earth. The acoustic properties seem quite comparable, but because structures with a low strength material are often dimensioned thicker, a raw earthen structure with thicker walls would naturally perform better in sound isolation.

The remaining five properties - recyclability, CO_2 emission, embodied energy, cost of material and local availability - are considered as the environmental characteristics, because they have a direct impact on the environment and an indirect impact on the design of the material. In this category, raw earth receives a relatively higher score compared to stabilised earth.

Based on the findings in Figure 22, it can be concluded that raw earth demonstrates better characteristics of comfort and environmental characteristics, while stabilised earth excels in structural characteristics. Consequently, the choice between stabilised and unstablised earth for constructing an earthen shell structure involves selecting a material that offers a comfortable natural indoor climate, has low costs, favourable environmental impact and recyclability but has poor durability and mechanical properties (raw earth), or a material that provides with superior durability and mechanical properties but with a relatively unfavourable environmental impact and the absence of a comfortable natural indoor climate.

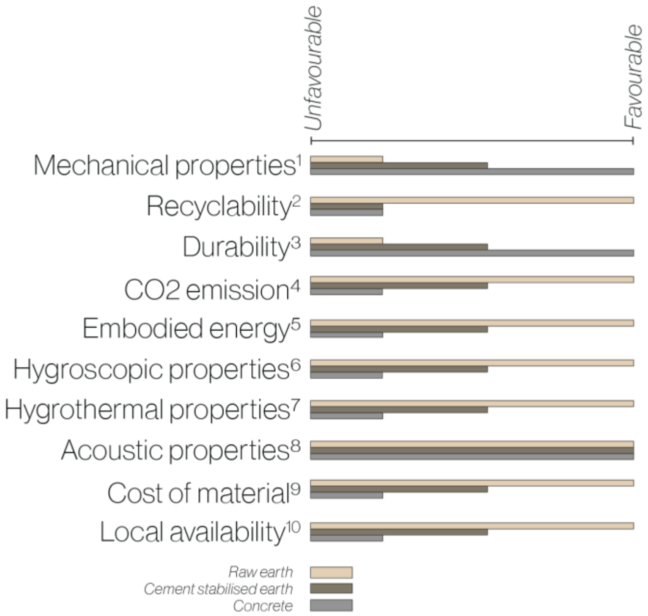


Figure 21 Characteristics of raw earth, cement stabilised earth and concrete, grouped by characteristic.
1. A. Curto et al., 2020, Heringer et al., 2019; Jaquin et al., 2009
2. Bruno et al., 2020
3. Bui et al., 2009
4. De Ávila et al., 2021; Minke, 2005
5. De Ávila et al., 2021; Minke, 2005
6. Cagnon et al., 2014; Arrigoni et al., 2017
7.; De Ávila et al., 2021; Arrigoni et al., 2017)
8. De Ávila et al., 2021).
9. Zami & Lee, 2010 ; Zami, 2021; De Ávila et al., 2021
10. Zami & Lee, 2010

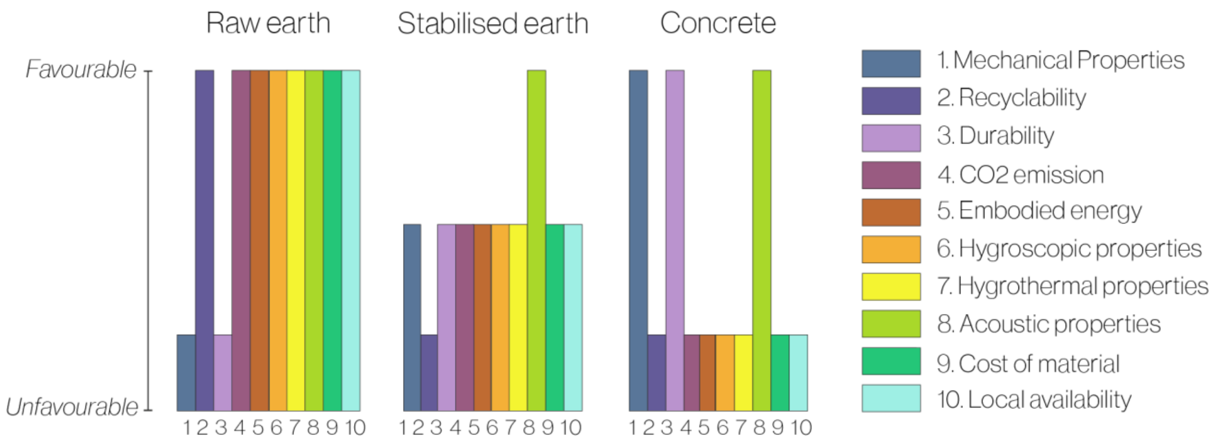


Figure 22 Characteristics of raw earth, cement stabilised earth and concrete, grouped by material.
1. A. Curto et al., 2020, Heringer et al., 2019; Jaquin et al., 2009
2. Bruno et al., 2020
3. Bui et al., 2009
4. De Ávila et al., 2021; Minke, 2005
5. De Ávila et al., 2021; Minke, 2005
6. Cagnon et al., 2014; Arrigoni et al., 2017
7.; De Ávila et al., 2021; Arrigoni et al., 2017
8. De Ávila et al., 2021
9. Zami & Lee, 2010 ; Zami, 2021; De Ávila et al., 2021
10. Zami & Lee, 2010

4.2 Fabrication of earthen shells structures

Based on the reviewed literature, it has become evident that fabric formworks show significant potential for constructing complex formed shell structures (Cauberg et al., 2012; Block et al., 2017; Popescu et al., 2018). Therefore, this analysis will take fabric formworks as the starting point. It is important to highlight that considerable attention has been devoted to the development of advanced methodologies for concrete shell structures, whereas there remains a significant gap in the corresponding research efforts for earthen shell structures.

When comparing earth with concrete, which is currently the most used material in sustainable fabric formwork shell structures, both materials offer versatility and the ability to be shaped freely. By comparing the contemporary fabrication methods of earth with those used for the shell structures, similarities can be identified. For example, the HiLo project utilised shotcrete, a technique where concrete is sprayed pneumatically. Similarly, the Terramia project, shot-earth was utilised, which is earth that is also pneumatically applied onto the fabric. Figure 23 and figure 24 provide a visualisation of the processes of applying shotcrete and shot-earth. Both stabilised and raw earth can be used for shot-earth fabrication method. With the aid of digital form-finding tools, design of material efficient shell structures is getting more accessible, allowing designers to create intricate shapes.

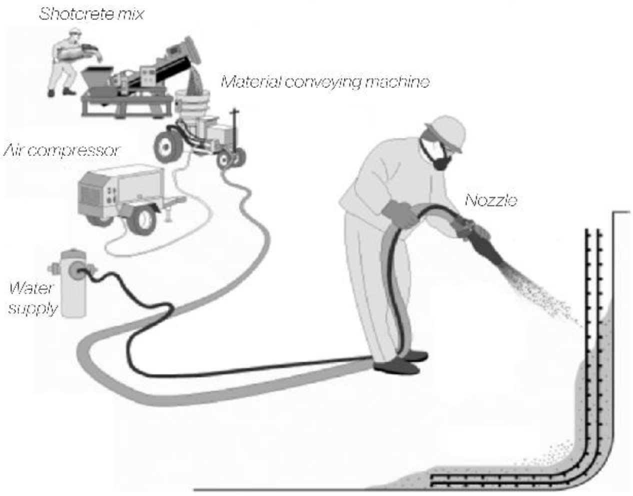


Figure 23 Dry mix processes of shotcrete From *"Shotecrete.org"* (https://shotcrete.org/why-shotcrete/process-dry-mix/)

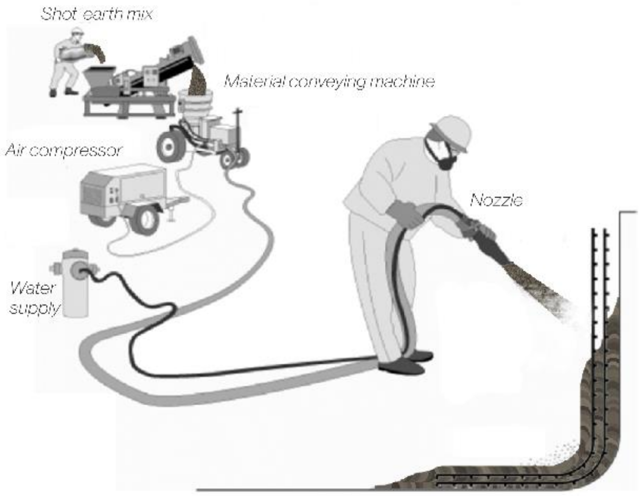


Figure 24 Dry mix processes of shot-earth. Based on image from *"Shotecrete.org"* (https://shotcrete.org/why-shotcrete/process-dry-mix/)

4.3 Applications of earthen shell structures

Based on the findings in sections 4.1 and 4.2, several conclusions regarding the potential applications of stabilised and unstabilised shot-earth structures in combination with fabric formworks.

Stabilised earthen shell structures have desirable characteristics for applications where durability is a priority, for instance in erosion-sensitive regions. The structures can offer relatively high strength, resulting in lightweight designs, which could be an important objective when constructing shell structures. However, their hygroscopic and hygrothermal properties are relatively unfavourable, considering that alternative climate regulation is necessary. Potentially, stabilised structures can be applied for exterior-only spaces. Additionally, the thinness of stabilised shell structures compromises their acoustic quality, and they generally have a larger environmental impact compared to unstabilised earth structures.

On the other hand, raw earthen structures require more maintenance due to weathering. Therefore, such shell structures could be applied in dry climates and indoor areas, protecting the structure from erosion or in free-standing areas, making it more accessible for maintenance. In temporary applications, made possible due to the recyclability of the material, this concern is lessened. Due to the relatively low strength of the material, the shells will have an increased thickness, which consequently results increased weight. The increased thickness of the material enhances the indoor quality by improving hygroscopic, hygrothermal, and acoustic properties. Furthermore, raw earth structures generally have a more favourable environmental impact. The utilization of local materials further increases the potential, particularly in remote areas. Unstabilised earthen shell structures can potentially be applied in remote areas, as substitute for tents, eco-lodges, tiny houses, garden houses.

Currently, shell structures serve as solutions for buildings that require large columnless spans, such as airports, theatres, or stadiums (see Figure 25). These structures are typically constructed using materials like concrete, glass and steel. The question whether earth can be applied in such contexts and if it would be advantageous. Given the need for high-strength materials in these long-span structures, the use of earth would result in significantly thicker shells, thereby increasing the amount of earth required. The question rises, whether such a structure remains favourable regarding the transportation costs, environmental impact, and net area utilisation, for instance.

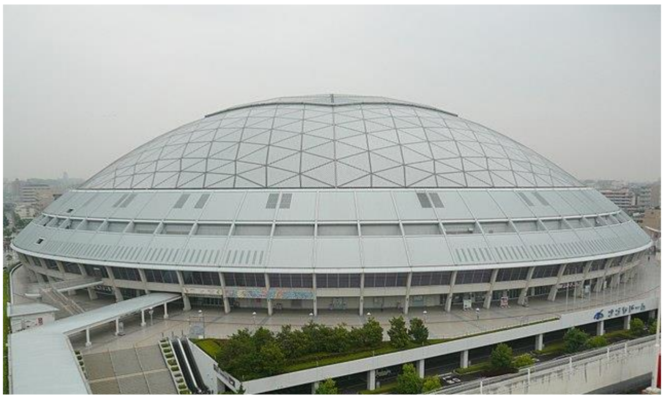


Figure 25 Nagoya Dome by Takenaka Corp. From *"Wikimedia Commons,"* by Gnsin, 2007 (https://commons.wikimedia.org/wiki/File:Nagoya_Dome_01.JPG). Licensed under CC BY 3.0

To illustrate the potential of earthen shell structures, two examples are presented below, showcasing the use of fabric formwork with both unstabilised and stabilised earth.

Example 1: Earthen humanitarian shelter

In February 2023, a devastating earthquake struck Turkey and Syria, resulting in the destruction of over 47000 homes (UNHCR, 2023). Such disasters create an urgent need for temporary housing to accommodate the victims.

Figure 26 Conceptual visualisation of earthen humanitarian shelters.

Traditionally, tents have been widely utilised as humanitarian shelters due to their quick assembly time. However, these tents often fall short in terms of providing adequate comfort for the occupants. Issues such as low sound privacy and poor thermal properties, particularly in regions characterised by significant temperature fluctuations, contribute to the discomfort experienced by the displaced populations. To enhance the living conditions of those in need, an alternative solution for humanitarian shelters could be the implementation of unstabilised earthen shell structures. These structures offer the potential to significantly improve the comfort and liveability of the temporary housing. A conceptual visualisation is presented in figure 26. Further research is required to examine the impacts of seismic forces.

Materialisation of earthen humanitarian shelter

By exploiting the properties of raw earth, such as its recyclability, acoustic insulation and thermal regulation capabilities, earthen shell structures have the potential to create more favourable living environments for displaced individuals.
The hygroscopic and hygrothermal properties of raw earth contribute to enhanced living comfort within the shells, particularly in regions characterised by significant temperature fluctuations. The higher mass of earth also improves acoustic isolation, increasing the privacy of the occupants.
The temporary character of the shelters diminishes the importance of maintenance, as they are not intended for long term use. Once the shelters have fulfilled their purpose, the material can be reused for other construction projects. Additionally, the affordability of earth is advantageous for humanitarian shelter initiatives, especially in a crisis situation.

Fabrication of earthen humanitarian shelter

First, local soil could be excavated from the surroundings. Second, (reusable) fabric formworks can be tensioned between supportive poles, allowing them to form a (anticlastic) funicular form. In locations prone to high winds or other external forces, additional reinforcement could be introduced into the structure. The next step is to apply the local soil onto the fabric, by spraying it with pneumatic force. Shot-earth is regarded as a relatively quick and relatively low labour-intensive method, particularly when automated robotic spraying is utilised. Furthermore, constructing multiple shelters can further reduce maintenance costs. See figure 27 for a potential fabrication method.

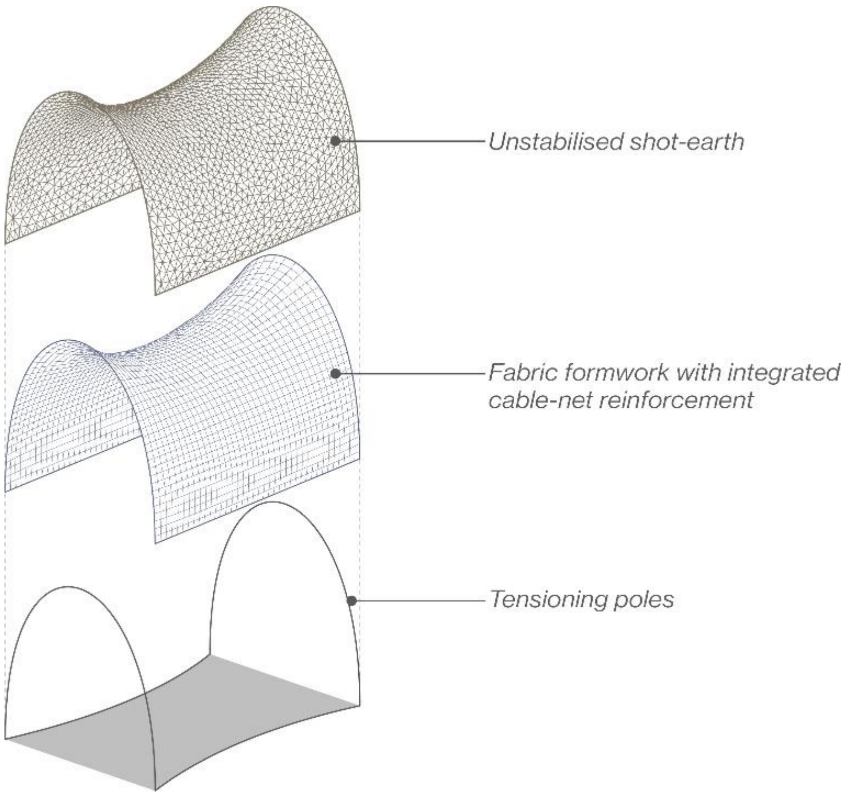


Figure 27 Layers of earthen humanitarian shelter concept

Example 2: Earthen extra-level penthouse apartment


Figure 28 Conceptual visualisation of earthen extra-level penthouse apartment

The Netherlands is currently facing a significant housing shortage, particularly in its major cities the shortage is projected to continue growing. To address this issue, the Dutch Ministry has set a target of constructing one million new houses by the year 2030. One potential contribution to the solution could be earthen shell penthouses on existing flat roofs. Research conducted by Rijksoverheid, the Dutch government, indicates that approximately 100.000 buildings in the country have the potential to support an additional level. Furthermore, this number could potentially increase when considering the use of lightweight material-efficient structures. While the demand for housing is high in the Netherlands, numerous projects are currently being put on hold or postponed due to issues related to nitrogen emissions. In this context, the use of earthen structure becomes particularly relevant as earth is a relatively sustainable material. By incorporating these structures into the urban landscape, they could not only contribute to the housing shortage, but also to solving various environmental problems. A conceptual visualisation is presented in figure 28.

Materialisation of earthen extra-level penthouse apartment

Although unstabilised earth possesses the advantageous characteristics of being fully recyclable and having a more positive environmental impact, the proposed recommendation for the construction of extra-level leans towards the use of stabilised earth, due to the higher strength and durability. However, stabilised earthen shell structures still could potentially be more economical and environmentally friendly than more traditional structures.

Fabrication of earthen extra-level penthouse apartment

In the context of constructing a penthouse apartment, the combination of shot-earth and fabric formworks show potential. Given the diversity of buildings, there is demand for various types of shell structures. Utilisation of digital form-finding tools facilitates the design of well-fitted apartments. In instances where complex forms are required, knitted formworks not only offer solutions shape-wise, but also for incorporating additional functionalities such as reinforcement, isolation material, ventilation, and electricity installations. On these knitted formworks, a thin layer of high strength concrete could be applied to support the earth that is sprayed on top. See figure 29 for a potential fabrication method.

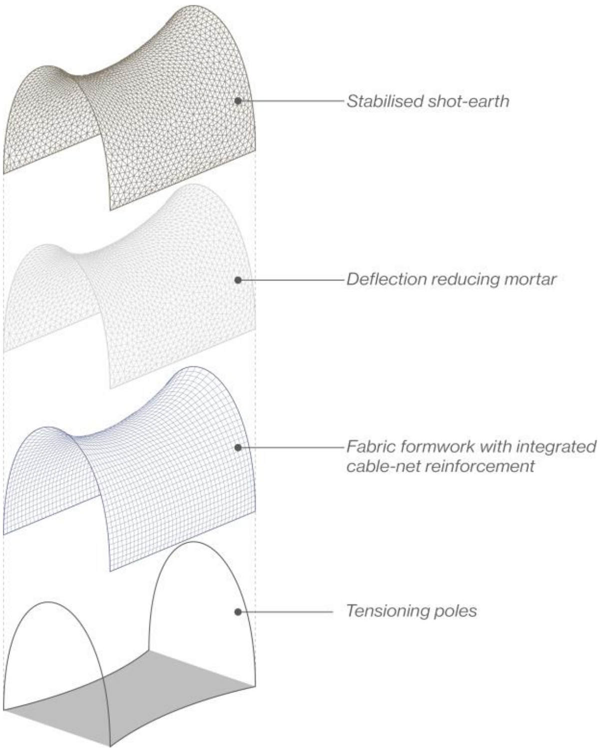


Figure 29 Layers of extra-level penthouse concept

5. Discussion

This chapter provides an analysis of the research findings by discussing the results. The main findings are derived from existing literature and reveal that both stabilised and unstabilised earth have distinct characteristics and corresponding applications. Stabilised earthen shell structures show potential for applications that have a more permanent and durable character. Unstablised earthen shell structures offer advantages in terms of hygroscopic and hygrothermal performance, recyclability, environmental impact, and local availability.

As the findings of the applications of earthen shell structures are quite specific, they can not be regarded as a replacement of traditional construction methods. The feasibility of using such structures heavily depends on local factors, including the local economy, availability of materials, and labour resources. Each project must be carefully assessed to determine if an earthen shell structure is a suitable option. However, because of the favourable properties of the material, earth could be considered as a potential contemporary construction material.

It is important to note that the specific mix of earth used in construction significantly can influence the properties and the performance of the resulting structures. Therefore, testing and evaluation of the chosen mix is essential to determine the most appropriate material for a given application. It is crucial to avoid generalizing the findings and to consider the specific requirements of each individual project. In further research, the combination of various materials could be considered.

As there is an abundance of literature on both shell structures as earthen construction, studying and analysing more literature is recommended for further research. However, it is also important to perform various testing and utilising various modelling techniques to expand the knowledge significantly and therefore increase the potential of earthen shell structures. Using digital structural analysis and various form-finding tools, the performance of earthen shell structures can be modelled. Furthermore, physical models can contribute additional information that may have been overlooked in the theoretical models. A proof-of-concept model could serve as an initial step towards the implementation of earthen shell structures in practice.

6. Conclusion

The objective of this paper was to explore the applications of earthen shell structures and assess their potential as sustainable and material. Based on existing literature the aim is to understand the current possibilities and limitations of earthen shell structures. By analysing available literature and linking characteristics of earthen construction and shell construction, the goal is to formulate potential applications. If applications could be found, earthen shell structures could potentially have an actual impact on the construction industry.

Through analysis of the characteristics of earth as a construction material, fabrication methods of earthen construction and fabrication methods of shell structures, supported by qualitative evaluation, various applications have been found. One of the findings is that stabilised earthen shell structures potentially have different applications than unstabilised shell structures. The findings of this study provide a conclusive response to the central question of this research paper, namely, “How can sustainable earthen shell structures be applied in practical contexts?”, can be answered.

Earthen shell structures can be categorised into two types: stabilised earthen shell structures and unstabilised earthen shell structures. Each type possesses unique characteristics, leading to different applications.

Stabilised earthen shell structures have a relatively high strength and great durability. Therefore, such structures could be applied in more permanent structures or in regions where maintenance is undesirable. The relatively high strength can result in relatively thin and lightweight structures. However, their hygroscopic and hygrothermal properties are relatively unfavourable, thus reducing its ability to naturally increase the indoor comfort. Potentially, such structures could be applied for exterior-only applications. An example of a sustainable extra level penthouse also shows potential as an application.

In contrast, unstabilised earthen shell structures have a relative low strength and poor durability. Therefore, such structures will need more maintenance due to weathering. Such structures could be applied in dry climates and indoor areas, protecting the structure from erosion or, in free-standing areas, making it accessible for maintenance. Due to the relative low strength, the shell structures need to be dimensioned relatively thicker and heavier. The increased thickness will enhance hydrothermal, hygroscopic, and acoustic performance. Furthermore, raw earth has a relative low amount of embodied energy, is recyclable and can potentially be locally sourced. Unstabilised earthen shell structures can potentially be applied in remote areas, or as substitutes for tents, eco-lodges, tiny houses, and garden houses.

For the fabrication method of earthen shell structures, it can be concluded that fabric formworks in combination with shot-earth show great potential, being a relatively sustainable, quick, and low labour-intensive fabrication method.

The results of this study indicate that in certain specific applications, shot-earth shell structures constructed using fabric formworks may serve as a viable alternative to conventional construction methods. However, it is crucial to conduct further research that encompasses both theoretical and practical aspects, including digital and physical testing and modelling. Through this comprehensive approach, earthen shell structures may emerge as a compelling outcome of the interplay between material-efficient construction techniques and sustainable materials.

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