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Rammed earth school in a Gambian context

A study of how rammed earth can be used as load-bearing material when constructing a school in The Gambia

Master's thesis in Master's Programme Structural Engineering and Building Technology

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CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2023
www.chalmers.se

MASTER'S THESIS 2023

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Master's Thesis 2023
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Cover: Rammed earth cylinders with two different soil mixes.

Typeset in L^AT_EX
Printed by Chalmers Reproservice
Gothenburg, Sweden 2023

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A study of how rammed earth can be used as load-bearing material when constructing a school in The Gambia

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Abstract

The aid organisation Eivor Björkman Gambia Aid are planning to build a school called Eivor Björkman Elementary in the neighborhood Brufut in The Gambia. The school is decided to be built with rammed earth as the load-bearing structure. In collaboration with Eivor Björkman Gambia Aid, Detail Group and Earth Lab Studio, this thesis is investigating how a rammed earth school can be built in The Gambia and what adaptations might be needed to the local context.

Through a pre-study about rammed earth and eight weeks of field studies in The Gambia, challenges regarding earth building in the Gambian context as well as a school context are identified and evaluated. The building process for rammed earth is evaluated through workshops in Sweden and The Gambia along with a test method developed and evaluated for achieving the compressive strength of rammed earth on site. Specimens made with earth from both Sweden and The Gambia are rammed and compression tested. A prototype of a shallow vaulted slab is constructed in collaboration with a compressed earth block entrepreneur. The prototype is built to assess if the design can be a possible slab option and how the building process would have to be adjusted to be used in a rammed earth building. Simplified calculations are performed for verification of suitability. Several uncertainties connected to construction in The Gambia are realized and discussed.

Common solutions to challenges are presented and possible adaptations to the Gambian context and the school context are presented before a final choice of solution is selected and motivated. It is concluded that one of the main challenges is protecting the rammed earth structure from water, especially during the rainy season. This is done by using a "boot" and a sufficient roof overhang. Another important aspect to consider is the erosion of the walls, which in the school context must be considered thoroughly to withstand children using the school.

Keywords: rammed earth, earth building, The Gambia, school, field study, conceptual design, compressive strength test, workshop.

Acknowledgements

There are many people who have been part of this project and made it possible to complete:

Firstly, we would like to thank Simon Rustas for the collaboration throughout the project, and for introducing us to this school project in the very beginning. We are very grateful for the cooperation in workshops, many discussions and the company, both before and during the field studies in The Gambia.

We would also like to give an immense thank you to Aisha Jobe, who welcomed us into her home and family and arranged our time in The Gambia. Our stay in The Gambia became much easier with your help arranging meetings, showing us around, getting food and having us experience the true Gambia. Without you, this thesis would not be the same.

A big thank you to Eivor Björkman Gambia Aid for allowing us to be part of the school project and helping us arrange the preparations for the trip. We are also grateful for the collaboration with Detail Group who has given us input about the design of the school, and EarthLAB Studio who have contributed with much knowledge and literature about rammed earth.

Alpha Omar Jallow has been of great importance by taking part in the prototype workshop and teaching us about compressed earth blocks, vaults and the construction process. Thank you for allowing us to do the workshop at your construction site and helping us with the needed tools.

We would like to thank Future in our hands The Gambia, especially Augustine Manneh, for informative meetings. Also Fake Bachata, Sanchaba Sulay Jobe Lower Basic School and Mbolo Association for the study visits.

Thank you AMU for arranging the rammed earth workshop in Sweden, allowing us to explore ramming on a larger scale.

Last, but not least, we would like to thank Shea Hagy and Robert Jockwer for the supervision and valuable input throughout the work with this thesis. Your help has been very useful to guide us through the twist and turns this thesis has taken.

Lena Allgurin & Linnéa Bjelkvik, Gothenburg, May 2023

List of Acronyms

CEB	Compressed earth blocks
EBG-Aid	Eivor Björkman Gambia Aid
EB-Elementary	Eivor Björkman Elementary
EPS	Expanded polystyrene
FIOHTG	Future in our hands The Gambia
MoBSE	Ministry of Basic & Secondary Education
NGO	Non-governmental organisation
PPP\$	Purchasing power parity dollar

Nomenclature

A	Area [m ²]
A_b	Equivalent compression area [m ²]
A_{ef}	Effective area under partially compressed area [m ²]
E	Modulus of elasticity [Pa]
H	Horizontal reaction force [N]
P	Point load [N]
V	Vertical reaction force [N]
f_a	Average compressive strength [Pa]
f_c	Unconfined compressive strength [Pa]
f_{cu}	Characteristic unconfined compressive strength [Pa]
g	Acceleration of gravity [m/s ²]
h	Height [m]
l	Length [m]
m	Weight [kg]
n	Number of specimen [-]
q	Distributed load [N/m]
γ_M	Material safety factor [-]
ε	Strain [-]
σ	Stress [Pa]
σ_{adj}	Stress adjusted to partially loaded area [Pa]
σ_{n-1}	Standard deviation [Pa]
Φ_b	Concentrated bearing factor $1 < \Phi_b < 1.5$ [-]

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1

Introduction

The Swedish aid organization Eivor Björkman Gambia Aid (EBG-Aid) is an organization working with health care and education in The Gambia. They are planning to build a new school called Eivor Björkman Elementary (EB-Elementary), in the neighborhood Brufut, The Gambia. The Swedish architectural firm, Detail Group, is developing a design of the school for the bought plot. The goal is to use local building techniques and materials found on site to construct EB-Elementary in an economical and sustainable way. Therefore, rammed earth is decided upon as the main building technique. EarthLAB Studio, an organization specializing in earth building and rammed earth, is also part of the project contributing with knowledge about the technique. Based upon the pre-set parameters, this thesis aims to investigate a possible rammed earth school in The Gambia in collaboration with EBG-Aid, Detail Group and EarthLAB Studio. Parts of the work is done together with the architecture student Simon Rustas.

1.1 Background

The use of earth as a building material has a long history all around the world. Different techniques have been developed and used i.a. cladding earth onto an underlying wall structure or constructing blocks with various ingredients. Rammed earth is one of the older, vernacular building techniques where earth material, from now on referred to as earth, is compacted into formwork to form a load-bearing structure with relatively high compressive strength. Furthermore, the compacted earth has beneficial properties regarding indoor climate and ecological sustainability. Two examples of old rammed earth structures are parts of The Great Wall of China and the city of Alhambra in Granada, Spain (Easton, 2007).

Earth is often transported away from the building site as excavation material, instead of transported to the site like other building materials. One large benefit of using rammed earth is that earth is available all around the world, and in optimal cases, the excavated earth from the building site can be used for ramming. This is beneficial today when the construction industry is facing a great challenge with building sustainable. Thus, the choice of rammed earth is tenable since it usually reduces transportation, reduces the impact of manufacturing the building material, and can easily be reused.

The Gambia is a small country on the west coast of Africa, see Figure 1.1. It spreads out around the Gambia river and is surrounded by Senegal, apart from the shore along the Atlantic coast. The country is about 11 300 km² (Globalis, n.d.). The country consisted of several kingdoms along the banks of the river and in the late 1800s it became a British colony (The Republic of The Gambia, 1988). It was surrounded by the French colony Senegal and remained a colony until its independence in 1965. The people of The Gambia are a mix of people from different tribes with various backgrounds and religions. It has influences from the African states prior to the colonization, the British domination, and the development of the country after autonomy. English is the official language in The Gambia, however, there are many local languages more commonly used, e.g. Wolof, Mandinka and Fula.



Figure 1.1: Map showing the location of The Gambia (Flappiefh, CC BY-SA 3.0 <<https://creativecommons.org/licenses/by-sa/3.0/>>, via Wikimedia Commons).

1.2 Aim and objectives

The overall aim is to identify challenges when building a rammed earth school structure and propose contextually suitable solutions. The solutions should be based on the findings and help the school project make well-informed design decisions in accordance to local conditions.

Research question:

- How do the local conditions impact the structural design of a rammed earth school building in The Gambia?

Sub-questions:

- What are the local earth properties and how do they influence the rammed earth structure?
- How can the structure be adapted to meet the local weather conditions?
- Does the design have to be adapted to a Gambian building process?

Objectives:

- Collect knowledge about rammed earth and how it is used today.
- Learn about the Gambian weather, culture and building techniques.
- Gain understanding of Gambian school environments and activities.
- Build prototypes and evaluate the building process.
- Identify construction challenges in the context.
- Propose adapted structural design solutions.

1.3 Demarcation

Some demarcations to limit the scope of the project are set:

- Other earth building techniques than rammed earth for the load-bearing walls are not considered.
- No cost or carbon-dioxide equivalent calculations or comparisons are performed for the conceptual design.
- Calculations presented in the thesis are simplified and used to get an estimation. More detailed calculations are required for the final design.

1.4 Method

The thesis is carried out in three different phases:

- Pre-study
- Field study
- Conceptual design

The initial pre-study phase aims to map rammed earth properties and how it is used today through a literature review. The ramming process is evaluated through theory as well as physical explorations. An initial perception of The Gambia, its culture, weather and construction industry is also obtained together with the state of the Gambian school system.

In the following phase, the Gambian context is explored through field studies in the urban area of The Gambia. Inspiration and knowledge about the Gambian context is collected through observations, study visits, a workshop and interaction with the local population. Further, the local earth properties are evaluated.

In the last phase, information and knowledge from the pre-study and field study is gathered and used to present conceptual design proposals handling challenges identi-

fied in relation to a rammed earth school. The knowledge from theory and practical experience from prototype building is implemented in the details and procedures of the construction.

1.4.1 Reading instructions

This report is divided into seven chapters where the **Introduction** gives an overview of the project and states the aim and research questions. Following is the **Pre-study**, which focuses on understanding rammed earth as a construction material, its structural challenges and possibilities. The chapter also addresses information about The Gambia to gain an initial understanding of the context of the country as well as the school context. The pre-study chapter includes insights from physical explorations from ramming and the development of a test method for testing compressive strength easily in The Gambia.

Continuing, the **Field study** presents findings from The Gambia. This chapter focuses on understanding the local context, partly through interactions with local constructors about standard processes, materials used and challenges faced. Interactions with locals about weather and culture are also presented to further capture the context. The understanding of schools and how they are used is evaluated through visits to existing schools. The Field study chapter also contains evaluation and results from material tests performed in The Gambia. The tests are carried out to investigate if the earth on site is suitable for ramming, or if it must be supplemented.

Following, the **Conceptual design** presents structural design suggestions based on the findings. The design suggestions take material properties, local conditions, and the construction process into account. The chapter, **Prototype of vaulted floor slab**, describes how a floor slab prototype was designed and constructed in The Gambia. Finally, the **Discussion** elaborates on the results of this thesis and the **Conclusion** summarizes the findings.

1.5 Social, ethical, and ecological aspects

By using local materials and building techniques, the project aims to be socially and ecologically sustainable, with the possibility of improving the local labor situation. The project is part of the revival of the old earth building techniques and can possibly be used to spread the usage of them, reducing the environmental impact of the construction industry in the country. Further, the United Nations has stated a Convention on the Rights of the Child where countries have agreed on children's rights and promised to protect them. The Gambia agreed to the convention in 1990 (Nderi, 2021). Some of these rights can be connected to the EB-Elementary that will be built in an area where there is no other school close by. By realizing the construction of the school, articles 17 *Access to information*, 28 *Access to education*, and 29 *Aims of education* can be enabled for the children in Brufut. Article 23 *Children with disabilities* and 31 *Rest, play, culture, arts* can be used to influence the design of the school (UN General Assembly, 1989).

2

Pre-study

This chapter presents information based on the literature review carried out before the field studies. Firstly, rammed earth as a building material and technique is described and possibilities and challenges are highlighted. Existing standards and guidelines regarding rammed earth are reviewed. Further, information about The Gambia and education in the country is presented. Finding possible parameters to take into account when designing is the main focus.

2.1 Rammed earth

Rammed earth is an old building technique, used through decades where knowledge has been passed down from craftsman to craftsman. In modern times, rammed earth is not commonly used but has lately been rediscovered as a sustainable and one hundred percent renewable building technique, given that no stabilizer is added. Earth is available almost everywhere in the world which makes it accessible to the common man, something that is important for the world's growing population. Old earth structures, e.g. the city of Alhambra, prove that it can be a durable material.

Earth can be used as load-bearing material and helps keep a good indoor climate. An earth structure's thermal mass helps keep a steady thermal climate and the earth can absorb water vapor from the surrounding air and keep a somewhat steady relative humidity. The ramming process is labor intensive, which can be expensive in the industrialized world today. However, in developing countries where unemployment is a problem, building with rammed earth could be an economical solution, since the building material is cheap and the labor relatively inexpensive.

2.1.1 Earth

Earth originally comes from the earth's crust (Minke, 2006). The bedrock erodes due to movements in the ground, such as thermal movements or freezing of water, and falls apart in particles of different sizes. Depending on the size of the particle, it is described as either clay, silt, sand, or gravel. Clay has the smallest particle size and acts as the binding agent since smaller particles have a bigger specific surface area, which leads to higher cohesive forces. The definition of the particle sizes for the earth components is found in Table 2.1.

Table 2.1: Components in earth and their particle size.

Earth component	Particle size [mm]
Clay	<0.002
Silt	0.002-0.06
Sand	0.06-2
Gravel	>2

There are different properties of earth that can be determined. Some of them are more relevant than others when used as a building material. According to Schildkamp (2009) the four most relevant earth properties are granularity or texture, compressibility, plasticity, and cohesion. Granularity describes the particle size distribution in the earth, while compressibility describes how well the earth can be compacted. Plasticity and cohesion are connected to each other, except plasticity describes how well the earth can be molded and deformed, while cohesion describes how adhesive the earth is, holding the particles together. These four earth properties affect the structural properties of the finalized earth structure and can be determined through earth tests either on site or with more accurate methods in laboratories.

There are different kinds of clay, some common types being Kaolinite, Montmorillonite, and Illite (Minke, 2006). These contain different minerals and are structured in varying lamellar structures, which results in varying cohesion.

2.1.2 Structural properties

When the earth is rammed and form a structural element e.g. a wall, the element's structural properties are of interest. Rammed earth is much stronger in compression compared to tension. According to Minke (2006), tensile and bending tensile stresses in earth structures should be avoided. As earlier mentioned, the structural properties depend on the earth composition but also the layer thickness and the ramming technique used.

2.1.2.1 Compressive strength

According to Fabbri et al. (2022) the compressive strength of rammed earth range between 0.3 to 7.0 MPa and depends on the molding water content, compaction energy, particle size distribution, clay content, and dry density. The compressive strength is directly proportional to the dry density, but the relation is unique for each earth mix. The unique properties make it hard to specify a standard strength applicable worldwide or even in neighboring regions. Fabbri et al. (2022) says that the “ideal scenario is to study the compressive strength of rammed earth experimentally for each instance the earth is used for construction” (p.128). This can be done by field tests or lab tests.

2.1.2.2 Tensile strength

If possible, tensile stresses should be avoided in rammed earth structures. Tensile strength depends on the quantity and type of clay as well as the water content in the mix. The tensile strength of dry rammed earth is about 10% of the compressive strength and ranges between 0.025 to 0.5 MPa (Minke, 2006).

2.1.2.3 Bending tensile strength

Bending tensile strength, similar to tensile strength, depends on the amount and type of clay. In studied bending tests, the lowest bending tensile strength reached 0.017 MPa with Kaolinite clay, and the highest strength, 2.23 MPa, was reached with Montmorillonite clay (Minke, 2006). In a study done by Otcovská et al. (2019), it is concluded, together with previous research, that a higher clay content gives an increased bending tensile strength and a decreased compressive strength.

2.1.2.4 Shear

Since rammed earth is built up in layers it is important to investigate the shear strength both within and in between the layers. Fabbri et al. (2022) discuss various studies and conclude that the shear strength can vary between 0.15 and 0.7 MPa and the shear modulus between 640 and 1582 MPa. It is found that the interfacial shear strength is 0.055 and 0.118 MPa for earth containing 17% and 20% clay respectively. However, in general little is known about how the clay content affects the shear strength. What can be concluded is that there is a significant difference between interface and intra-layer properties that must be considered when constructing with rammed earth. The shear strength should be evaluated through lab tests to gain the correct properties.

2.1.3 Building process

When building with rammed earth it is important to primarily prepare the site and perform earth tests to obtain a good earth mix. Secondly, construct a formwork of desired shape and finally compact the earth into the formwork. In this section, the different stages in the process are described more in detail.

2.1.3.1 Earth tests

Earth tests can be carried out in a lab for more detailed specifications regarding the properties of the earth mix. Still, there are several tests that can be done on site with rather easily accessible tools to get coarser results.

Two commonly used earth tests performed on site are jar test and ball drop test, see Figure 2.1. The jar test is used to evaluate the particle size distribution of the mix by filling one third of a transparent jar with earth, and then add water to the top. The jar is thereafter shaken thoroughly to separate all the particles from each other

2. Pre-study

and left for 24 hours for the particles to settle in different layers. The larger the particles, the faster they fall to the bottom of the jar. After about 24 hours, different layers can be seen, with the clay layer on top followed by the silt and sand, see Figure 2.1a. Thus, the relation between the different particle sizes can be found for the earth mix. The test can however be somewhat misleading due to voids between particles, causing the layers to not fully represent the actual volumes. Therefore, it is used as a field test and if more precise relations are desired lab tests are needed.

The ball drop test is used to find the right moisture content of the earth mix. It is an easy and quick method to evaluate the current mix when ramming. A ball of the earth mix is formed by hand and thereafter dropped from a height of about 1.5 m. When the ball lands, the way it breaks indicates its moisture content. If the ball breaks into many small pieces, the mix is not moist enough. If the ball does not break at all, it is too wet, while if it breaks into a few large pieces, the moisture content is good, see Figure 2.1b. However, if the ball breaks into many small pieces, the mix can have enough water, but be too sandy. In a similar manner, if the ball does not break at all, the earth can be either too wet or contain too much clay. It is therefore preferred to perform a jar test before executing the ball drop test.



(a) A jar test showing different layers of the earth mix.



(b) A ball drop test result of mix considered suitable for ramming.

Figure 2.1: Two common field tests of earth mix.

2.1.3.2 Formwork

To construct anything in rammed earth, a formwork is needed. Most common is to use wood or steel but other materials can be used as well. A typical formwork con-

sists of surface material that is stabilized in both horizontal and vertical direction to prevent bulging. The formwork is preferably lightweight and easy to assemble, disassemble and reuse. EarthLAB Studio has created an example of efficient formwork in wood, without fasteners, that can be moved upwards and sideways to build up the wall in segments, see Figure 2.2. The formwork was created out of a research project called In-Form (EarthLAB Studio, n.d.).



Figure 2.2: Picture showing formwork developed by EarthLAB Studio in use. The form can be moved upwards and sideways along a wall.

2.1.3.3 Ramming process

According to Easton (2007), the ramming technique is equally important as the earth mixture to obtain an optimal rammed earth structure. The ramming can be carried out either with a traditional heavy wooden rammer or a slightly more modern steel rammer. The steel rammer consists of a steel plate welded to a steel pipe where the weight of the rammer can be adjusted by filling the pipe with sand. A rammer can also be constructed with heavy materials found on site, see example in Figure 2.3. When compacting the earth, the weight of the rammer should be utilized. The rammer should be raised approximately 30 to 45 cm and then dropped onto the earth. Using a rammer of this kind is labor intensive and today some rammed earth constructors use air compressors to speed up the ramming process. It is partly the force, but also the vibrations created, that compacts the earth. The goal is to move the particles into the densest possible position to achieve maximum strength and prevent water from intruding into the structure. The best way to compact the earth is therefore a repeated thumping.



Figure 2.3: Example of homemade rammer consisting of a broom stick with a dumbbell attached at the bottom.

When starting ramming, a layer of earth is placed into the formwork and compacted. The compaction should begin along the formwork edge and finish in the middle to reduce stresses on the formwork. When the earth is compacted to approximately half of the original volume, a change in sound can be noticed according to Easton (2007). The sound is reverberating from the formwork and indicates that the earth is fully compacted. Some earth constructors prefer standing on top of the structure and begin each layer by walking on the structure to make it settle before using the rammer.

There are studies evaluating how layer thickness influences compressive strength. The studies are done on stabilized rammed earth but according to Fabbri et al. (2022) the findings are applicable also to unstabilized structures. The optimal layer thickness is found to be 100 mm with thicker layers resulting in lower compressive strength. Further, layers rammed in the bottom are found to be stronger than the top layers (Easton, 2007). This is due to the surcharge force coming from ramming superimposed layers, resulting in even better compaction of the bottom layers. One should therefore be extra meticulous when ramming the top layers.

When the structure is rammed, it should be left to dry before loading. The strength of rammed earth increases with drying time. According to Erden (2022), the drying time should be about four to six weeks, depending on the thickness of the element.

2.1.4 Long-term effects of rammed earth

Rammed earth is subjected to long term effects, one of them being shrinkage. The shrinkage is 0.25% to 1% and can occur due to high clay content (Erden, 2022), (SADCSTAN, 2014). To reduce the shrinkage, the clay content can be reduced. If the weather is dry and warm and the air moves sufficiently it takes just a few days for the shrinkage to stop (Minke, 2006).

Most rammed earth walls are rammed in sections that dry and shrink while the next section is rammed (Minke, 2006). This shrinkage causes restraints for the connecting section, which can result in shrinkage cracks. These cracks can cause severe damage to the structure if capillary water can enter the cracks. A solution can be to apply a lime mortar between the sections rammed at different times. The mortar has a slower drying period and remains plastic until the ramming process can continue. Shrinkage cracks can occur in all directions, not just between layers. If cracks appear, the wall should be rendered or the cracks filled (SADCSTAN, 2014).

Similar to concrete, rammed earth shows creep deformations when loaded over time (Erden, 2022). The creep is 0.02% and should be considered when designing the structure.

2.1.5 Erosion

Rammed earth is water soluble, which makes it erode when water flows along its surface (Erden, 2022). The water washes away small particles and gives it a rough look where greater particles are visible. After a few years, the erosion stagnates due to the change of surface roughness. When parts of the wall are washed away the wall loses strength. Therefore, rammed earth structures have to be protected against erosion and contact with water in general.

Erden (2022) writes that one way to take erosion into account is to use *calculated erosion*. This is a method where the wall is made 2-3 cm thicker to allow for erosion. The eventual change of surface roughness hinders the water flow along the surface from removing more particles. Using *erosion breaks* is an alternative solution where tiles are placed horizontally in the wall every 40-50 cm. The erosion breaks aim to reduce the velocity of the water along the surface, hence the erosion is slowed down.

2.1.6 Protection against water

When designing the structure, it is of great importance to protect it from water. This as water dissolves the rammed earth. Protection of structures can be done by using a boot, coat, and hat (SADCSTAN, 2014). The boot aims to protect the lower part of the structure against the splashback of rain by making the lower part of the wall water-resistant. Examples of solutions are rendering the surface, using bricks or stone as protection, or adding a stabilizer to the lower part of the wall. Another approach is to add an extra layer of rammed earth in the bottom and replace it when eroded. The coat refers to protection against driving rain that can

cause erosion of the walls. A possible solution can be to coat the wall surface with a protective coating. The coating should preferably maintain the vapour permeability of the rammed earth and be flexible enough to follow the shrinkage of the earth (Walker et al., 2005). Examples of coatings are lime renders, liquid silicate solutions or linseed oil. Finally, the hat aims to protect the upper part of the structure with an overhanging water-tight roof. The longer the overhang, the greater area of the wall is protected. According to the guidelines from SADCSTAN (2014), a wall height of three times the depth of the overhang is sufficiently protected.

2.1.7 Existing standards and guidelines

Rammed earth as a building technique was used long before building standards and norms were developed. In some countries, there are building standards for earth structures, for example in Germany and South Africa. However, in many parts of the world, there are no well-developed norms or standards for designing and building with the material.

Matsdotter (2020) describes in her master's thesis that one drawback when building with earth is the "lack of scientific basis, regulations and standardization applicable to other conventional construction materials" (p.16). Matsdotter claims that the rammed earth regulations are most highly developed in New Zealand and Germany.

In a comparison made by Lee (2020), it is said that "earth has never been a part of the industrialization process of architecture. Therefore, in order to make earth prolific in modern architecture, it is imperative to go through the process of legalization via standardization of materials and technologies that the so-called industrial materials must-have." (p.1). When comparing standards and codes for building with earth, Lee (2020) limited the comparison to codes in Germany, New Zealand, India, the USA and Zimbabwe, which all include the rammed earth technique. All the countries have authorized laws that can be categorized into four parts: earth, building material, building system, and general requirements. Even though the particle size distribution was stated as the most important property of the earth, test methods for determining the particle size distribution were, according to Lee, unclear, and simple field tests were often used. At the building material stage, compressive strength is stated as the most important property in all five codes. The codes have differing views on adding stabilizers to the earth mix. Germany and New Zealand are the only countries proposing working without stabilizers while the codes in India, the USA and Zimbabwe require adding cement and lime. In India, the code allows adding straw to the earth mix to stabilize the material.

On the building system level, the importance of shear strength to withstand horizontal forces such as wind was stressed (Lee, 2020). The earth itself does not necessarily have to take shear forces but the structural system in full must withstand all forces acting on the structure. The codes also emphasize the importance of protection against water in all forms since water is a threat to earthen structures. All standards provide details to prevent erosion. In New Zealand, India and Zimbabwe, the

possibility to withstand water should be verified through tests such as spraying or dropping water on the earth structure. In countries where earthquakes are a possible problem, e.g. New Zealand, India and the USA, seismic design is included in the building codes. The building codes focus on the earth structure and commonly take openings into account but only briefly touch upon connecting structures such as roof, ceiling and floor and how they should be connected to the earthen structure. The design of the formwork and how it should be used is only mentioned in the Zimbabwe code, even though the formwork greatly impacts the final structure. Maintenance of the earth structure was not covered in depth in any of the codes and only some of the codes recommended painting or plastering in the construction stage.

2.1.8 Comparison with conventional building materials

When comparing earth with other building materials that are more commonly used in the industrialized world, it can be concluded that earth has the lowest load bearing capacity in both compression and tension but is beneficial in other aspects. In Table 2.2 material properties of rammed earth, concrete, wood and brick are listed with data from Olsson (2022).

Table 2.2: Properties of earth structures compared to conventional building materials. Data from Olsson (2022).

Material properties	Rammed earth	Concrete	Wood	Brick
Density [kg/m^3]	2250	2200	500	1500
Compressive strength [MPa]	0.5-5	10-130	7-64	12-65
Tensile strength [MPa]	0.2-0.5	1-10	2.5-165	1.2-13
Shrinkage ratio [%]	0.5-2	0.04-0.08	-	-
Drying period [$days$]	28-42	28	-	-
Thermal conductivity [W/mK]	1.0	1.7	0.14	0.7
Specific heat capacity [kJ/kgK]	1.0-1.2	1.0	1.6	1
Embodied energy [$kgCO_2eq/m^3$]	9.3	229	-680	565.2

Earth has equally high specific heat capacity as concrete and bricks, which means it requires the same amount of energy to heat the building. Rammed earth have lower thermal conductivity than concrete, hence, heat is transported slower through the material which dampens the heat fluctuation inside a building. Regarding embodied energy, rammed earth has a low value compared to concrete and brick. Wood has a negative value since it captures CO_2 while growing. Further, earth is 100% recyclable which means that it can be reused without losing quality if no stabilizer has been added.

2.2 The Gambia

The Gambia is located below the Sahara Desert, along the Gambia River with Senegal surrounding the country. Possible aspects to consider regarding the Gambian climate, history of its building industry and education are presented in this section.

2.2.1 Climate in The Gambia

The Gambia has a sub-tropical savanna climate with a rainy season from June to October (The Republic of The Gambia, 1996). The temperature differs slightly between the coastal areas and the inland, with a mean temperature between 18 °C and 30 °C during the dry season from November to May (The World Bank Group, 2021b). During the rainy season, the mean temperature ranges between 23 °C and 33 °C. Overall, the mean temperature in the country as well as the minimum temperatures has increased over the last 60 years. During the rainy seasons most of the country's precipitation is received, a yearly average between 700 and 1000 mm. Similarly to the average temperature, the average precipitation amount has changed over time resulting in shorter rain seasons with less rain. Compared to Sweden, the average amount of yearly precipitation is about the same, approximately 700 mm, though in Sweden, this is more evenly distributed over the year (The World Bank Group, 2021a).

2.2.2 Significant natural hazards in The Gambia

The World Bank Group (2021c) defines some significantly hazardous weather conditions occurring in The Gambia. The most common hazard is flooding, both of the Gambia River and along the Atlantic coast. Each year about 20% of the country is flooded, and larger flooding occurs occasionally affecting many of the inhabitants. The Gambia Standards Bureau (2018) states that flooding is a “Very serious and urgent problem...” (p.15).

2.2.3 History of the Gambian building industry

The Gambia is a rather poor country with a gross domestic product per capita of 2 270 PPP\$ in 2022, compared to Sweden with 53 300 PPP\$ (Gapminder, n.d.-b). According to The Republic of The Gambia (1996) the incomes in the country were low in 1996 compared to the costs of housing due to high construction costs. The high construction costs can be derived from the high costs of importing building materials. A large proportion of the building materials used before 1996 were imported, causing expensive constructions where most of the money used left the country. In 1991, over 10 million US dollars left The Gambia due to import of construction materials. To reduce this, a suggestion was presented in the report to keep the money within the domestic economy. It proposed importing less building materials and instead using locally available materials and encouraging the local material industry.

Another influencing parameter for the lack of use of local building materials was, according to a report from The Republic of The Gambia (1996), the building regulations which were complex. The report says that the standards were set high and complicated to combine with the use of local building materials. The standards were evaluated and changed in 1995 to add more flexibility and benefit the use of local building materials and receive a building standard that would be more achievable to the poorer population.

The existing construction labor in The Gambia can also be seen as part of the difficulties regarding the history of The Gambian construction industry. The report by The Republic of The Gambia (1996) states that imported construction materials and high standards required workers skilled in the more complicated procedures used. This limited the supply of suitable workers, while there was a large portion of workers available with less skills in these techniques.

2.2.4 Education in The Gambia

The Republic of The Gambia (2002) states in its constitution that “All persons shall have the right to equal educational opportunities and facilities...” as well as “...basic education shall be free, compulsory and available to all” (p.15). It also states that disabled persons should not be discriminated regarding the availability of education. The education in The Gambia has traditionally been through verbal instructions and imitation (The Republic of The Gambia, 1988). Nowadays, visual arts are part of education as well as education in local languages and cultures. According to The World Bank (2022), 73% of the youths aged 15-24 in The Gambia could read and write in 2021. Data from Gapminder (n.d.-a) shows that 85.2% of primary school aged children completed primary school in 2021.

2.3 Physical exploration

In this section, explorations of the ramming process and performed tests for evaluating structural properties are described. The ramming process is assessed through ramming projects of different sizes to gain experience and a feeling for the material and the technique. A test method for evaluating compressive strength that can be utilized on site in The Gambia is developed.

2.3.1 Exploration of ramming process

Initially, small samples were rammed with earth mixes of different clay content to get a feeling for different mixes and how they appear and behave. The ramming process, consisting of i.a. earth mixing, earth testing, and ramming were explored. Later, a wall with an arch opening was rammed. The goal was to get an understanding of the process in a larger scale and identify challenges along the way. An arch was created in the wall to evaluate the arch technique as an alternative way to create an opening.

2.3.1.1 Earth mixing

Three mixes containing 10%, 15%, and 20% clay were prepared. The clay content was adjusted by mixing clay with crushed stone and gravel, all bought in a store to ensure that the correct clay content was achieved. It was noticed that a mix with higher clay content feels more sticky while less clay gives a sandy feeling.

When mixing the earth for the wall, clay was taken from a gravel pit outside of Gothenburg. Some obstacles were met that had not been discovered when mixing the smaller samples. It was more challenging to mix wet clay with gravel. The clay was wet and cloddish from the beginning and despite the fact that a concrete mixer was used, it was much harder than mixing dry ingredients. In this case, the mix was also too wet, so it had to be dried before it could be used. The cold and rainy weather at the time made it difficult and time-consuming to dry the earth.

2.3.1.2 earth testing

One of the biggest challenges when ramming was to find the right mix. The jar tests gave a good indication of how much clay and silt the mix contained in total, but it was noticed that the line in between the clay and the silt layers can be difficult to identify. A large amount of earth was mixed, with an aim of 15% clay content. As can be seen in Figure 2.4, the clay and silt together is clearly higher than 15%. Since the jar test takes approximately 24 hours to settle it is hard to fine-tune the mix while mixing.



Figure 2.4: Jar test of the earth used for ramming the wall.

The ball drop tests gave a quick result indicating the moisture content. It was

noticed that the difference between a too sandy and a too dry mix was hard to distinguish from the ball drop test. The result also deviated significantly if a clay clod was present in the ball. It was discovered that it can be beneficial to make several ball drops of the same mix to reduce the uncertainties and conclude that the mix is suitable for ramming.

2.3.1.3 Ramming

During the small ramming tests, it was noticed that the formwork easily moves upwards from the base plate causing the earth to “leak”, if the form is not entirely fastened to the bottom.

When ramming the large wall, see Figure 2.5a, the formwork had to be moved upwards. The importance of placing the formwork completely vertical was discovered. In this case, the upper part of the wall became slightly tilted due to the formwork being heavier on one side, which was not realised until afterwards. This can be seen in Figure 2.5b. The formwork should preferably not cover any part of the opening where the earth is poured and rammed. This formwork had a part going across the opening, see Figure 2.5c, which resulted in uneven ramming due to difficulty of ramming below the formwork piece.

During the ramming, a slight difference in sound from the ramming was noticed. When the earth had been compacted, the sound changed from rather muffled to more reverberation from the formwork. This made it possible to hear when the earth was compacted enough.

For the arch opening, the catenary curve was used to achieve an efficient shape. To ensure that the formwork can be removed, two wood pieces can be pushed into the opening in the arch form, causing the form to “fall” slightly and be released from the wall. The arch-formwork was kept within the wall during the drying time.



(a) Rammed earth wall with internal arch. The picture is taken just after ramming, with the arch-form still in the wall.



(b) Wall from the side. The upper part is slightly tilted due to formwork not being completely vertical.



(c) Part of formwork covering the opening.

Figure 2.5: Pictures of the rammed wall.

2.3.2 Initial evaluation of test equipment

The first test was conducted to evaluate the function of a self-built test equipment as well as to evaluate how the clay content affects the compressive strength of a rammed earth specimen. The tests were carried out at Chalmers on the 3rd of February.

2.3.2.1 Test equipment

The tests were conducted with the self-designed test device, built by Simon Rustas, see Figure 2.6a. The equipment consists of a compression plate where the force is applied to the specimen by tightening a screw-nut along a rod, pushing the compression area downwards. The rod is connected to a scale that shows the force applied. Under the specimen, wood blocks are used to reach the desired height.

2.3.2.2 Test method

Three rammed blocks were tested, containing 10%, 15%, and 20% clay respectively. The blocks were left to dry for eight days at room temperature before being tested in compression. A steel plate was used to distribute the force over a 6x6 cm area, see Figure 2.6b. The applied force on the specimen is calculated through equilibrium according to Equation 2.1, including the relation between the lever arms of the test equipment. The calculation procedure can be found in Appendix A.



(a) Self-designed test device, built by Simon Rustas.



(b) Steel plate applying the load to the specimen.

Figure 2.6: Testing configuration.

$$P = m * g * \frac{65.5}{12.5} \quad (2.1)$$

where: P = point load [N]
 m = weight showed on scale [kg]
 g = acceleration of gravity [m/s^2]

Observations were noted during testing and an equivalent compression stress was calculated according to Equation 2.2. Since the block is only partially loaded, Swedish Standards Institute (2008) (p.111) is used to calculate the adjusted compressive stress, see Equation 2.3 and Figure 2.7.

$$\sigma = \frac{P}{A} \quad (2.2)$$

$$\sigma_{adj} = \frac{P}{A \cdot \sqrt{\frac{A_{ef}}{A}}} \quad (2.3)$$

where: σ = stress [Pa]
 P = point load [N]
 A = area [m^2]
 σ_{adj} = stress adjusted to partially loaded area [m^2]
 A_{ef} = effective area under partially loaded area [m^2]

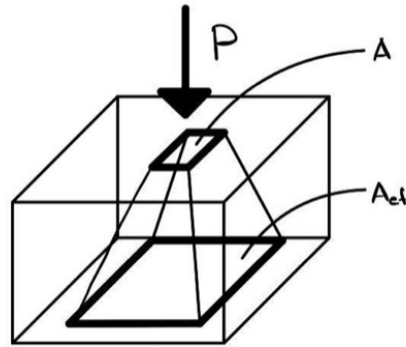


Figure 2.7: Compression stress on partially loaded area.

2.3.2.3 Results

The cracking loads and the failure loads of the blocks can be seen in Table 2.3. The 15% block reached failure at a load of 8.75 kN. For the 10% block and the 20% block, compression failure was never reached due to lack of possibility to increase the load further with the testing device, as the bolt was too short.

Table 2.3: Compressive stress for blocks with various clay content.
Test 1 - 03.02.2023

		Compression		
		P [kN]	σ [MPa]	σ_{adj} [MPa]
10 %	Crack	8.64	2.4	1.1
	Max load, no fail	9.00	2.5	1.2
15 %	Crack	7.15	2.0	0.92
	Max load, fail	8.75	2.4	1.1
20 %	Crack	6.64	1.8	0.85
	Max load, no fail	9.26	2.6	1.2

2.3.2.4 Discussion

Overall, during the compression tests, the cracks appeared at the top and grew downwards when the load was increased. Cracks were seen in the 20% block before testing. Since the clay content was higher in that earth mix, some cracks might have appeared due to shrinkage, or from moving the specimen. Therefore, it was not entirely clear when it started to appear new cracks and when the already existing cracks started growing. There was however one crack that was visibly larger than others after the compression test was performed. In the same specimen an elastic deformation was observed. The side surface was bulging out when under high compression but most of the deformation was drawn back when unloaded.

The test equipment worked well overall. However, the rod where the load was applied by tightening a screw-nut was too short to achieve a load high enough to break all

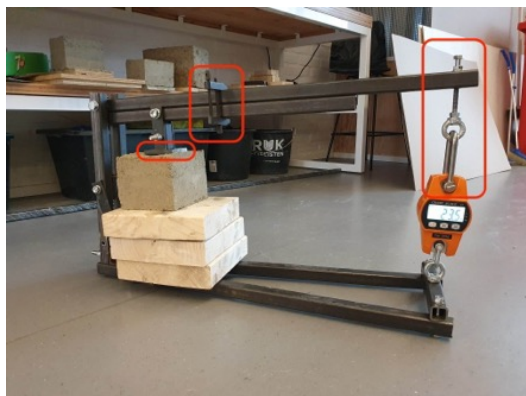
the specimens in compression. This resulted in two test blocks not failing. For future tests, higher forces are desired to reach compression failure for all specimens, which can be done by extending the length where the nut can be screwed or by reducing the steel plate area.

2.3.3 Second evaluation of test equipment

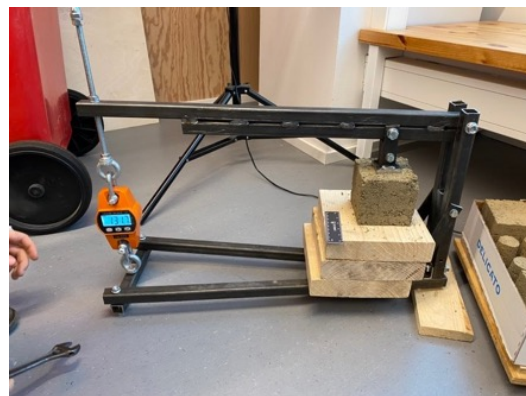
A second test was performed at Chalmers on the 14th of February. The compressive strength and the stress-strain relation for four different earth mixes was evaluated. The four mixes contained 10%, 15%, 20%, and unknown% of clay. Further, a new calculation method for calculating adjusted compressive strength from a partially loaded area was tested and evaluated.

2.3.3.1 Test equipment

Some alterations were made to the test equipment after the first test. Two of these were increasing the length of the rod as well as decreasing the anchoring loops attached to the scale. This was done to increase the possible tightening of the test equipment and thereby increase the applied load. Another alteration made to gain higher compressive stresses was to reduce the steel plate size from 6x6 cm to 4.5x4.5 cm. The two steel pipes forming the lever arm were welded together instead of clamped to decrease the loss of force to shear movements between the pipes.



(a) Old test equipment where parts to be changed are highlighted.



(b) Updated test equipment.

Figure 2.8: Comparison between old and new test equipment.

2.3.3.2 Test method

Two small cylinders and one block from each mix was rammed and left to dry at room temperature for eight days before being tested. The whole cross section of the cylinders were loaded, the compression stress is therefore calculated using Equation 2.2.

The unconfined compressive strength for the blocks, f_c , is the recalculated stress taking the material outside of the compression area into account. This was done according to Appendix C in Walker et al. (2005), see Equation 2.4. Φ_b is a factor taking the geometry outside of the compression area into account. The factor should be between 1 and 1.5. In this case 1.5 is used to be conservative, assuming failure just below the compression plate. γ_M is a material safety factor depending on the experience of the workers and the test method used to determine the earth properties. For this case, the factor is set to 1 since the material capacity should be calculated without safety factors.

The height of the specimen was measured step-wise during loading, using a vernier caliper. The heights were compared to the initial height to obtain the strain.

$$f_c = \frac{P \cdot \gamma_M}{\Phi_b \cdot A_b} \quad (2.4)$$

where: f_c = unconfined compressive strength [Pa]
 P = point load [N]
 γ_M = material safety factor [-]
 Φ_b = concentrated bearing factor $1 < \Phi_b < 1.5$ [-]
 A_b = equivalent compression area [m²]

2.3.3.3 Results

The results from testing are presented below together with observations. In the following table, Table 2.4, the failure loads for the cylinders are presented, while in Figure 2.9, the stress-strain relations for the two cylinders of each mix can be seen. All the result data is found in Appendix B.

Table 2.4: Failure loads for cylinders. Test 2 - 14.02.2023.

		Compression		
		P [kN]	σ [MPa]	σ_{mean} [MPa]
10 %	Cylinder 1	1.90	1.77	1.75
	Cylinder 2	1.85	1.72	
15 %	Cylinder 1	1.90	1.77	1.41
	Cylinder 2	1.13	1.05	
20 %	Cylinder 1	1.34	1.24	1.44
	Cylinder 2	1.75	1.63	
Unknown %	Cylinder 1	1.34	1.24	1.58
	Cylinder 2	2.06	1.91	

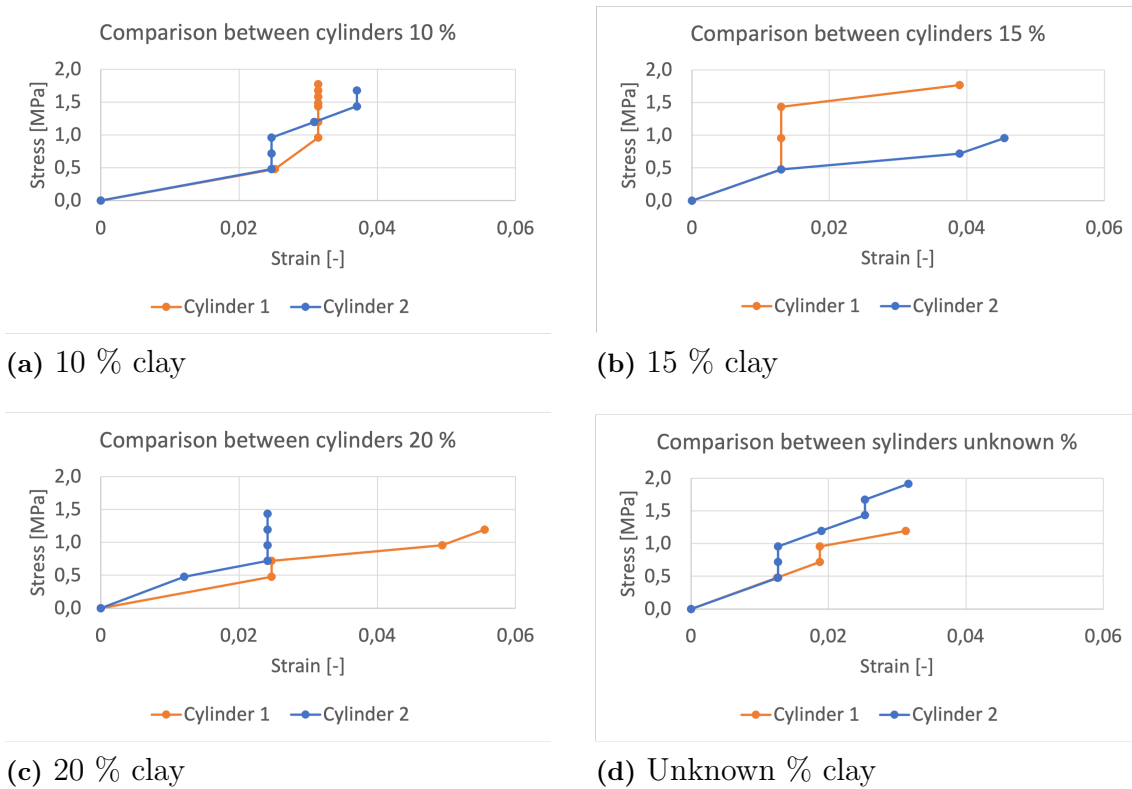


Figure 2.9: Result showing stress-strain diagrams for the two cylinders of respective mix.

One of the cylinders of unknown % of clay cracked between the layers when lifting the specimen before testing. The layers in this specimen were clearly visible and relatively thin. The parts were stacked on top of each other and tested in the same way as the other cylinders. The compression strength of this cylinder was the highest of all cylinders, reaching 1.9 MPa. After unloading, it was noticed that the specimen was broken between more layers than from the beginning, the cut being close to perfectly flat between the layers.

In Table 2.5, the failure loads for the blocks can be found. All the blocks were loaded until failure and tended to crack at the corners of the compression plate of the test equipment. The 10% and 15% blocks had compressive marks of about 2 mm when unloading the blocks, while the other two blocks barely had any marks.

Table 2.5: Failure loads for blocks. Test 2 - 14.02.2023.

	Compression		
	P [kN]	σ [MPa]	f_c [MPa]
Block 10%	5.92	2.92	1.95
Block 15%	8.75	4.32	2.88
Block 20%	7.72	3.81	2.54
Block Unknown%	6.43	3.18	2.12

In Figure 2.10, the jar tests for the 10%, unknown % and 15% mix show that the unknown mix has the most clay. The 15% mix correlated relatively well and showed a result of 18% clay. The 10% mix indicated a clay content of 16% while the unknown mix showed a result of 24% clay.



Figure 2.10: Result of jar tests with different clay content, 10% clay to the left, unknown clay content in the middle, 15% to the right.

2.3.3.4 Discussion

When performing the tests, it was seen that the strain sometimes changed drastically and sometimes not at all. It was therefore challenging to conclude anything about the modulus of elasticity. The number of measuring points was deemed insufficient and the measuring method was not precise enough. An improvement would be to have more measuring points.

What can be seen from the results of the tests is that there are many parameters affecting the compressive strength. The ramming is influencing as well as the particle sizes and its distribution within the specimen. If there are large particles, it has more impact on the tested strength of the smaller cylinders, compared to the bigger blocks, since the particle takes up a bigger portion of the cross sectional area.

The cylinders showed different failure modes. In some specimens, the failure occurred through crushing over the entire cross-section of the element, see Figure 2.11a. For other specimens, a diagonal shear failure occur, see Figure 2.11b. Although, most specimens had a failure mode somewhere in between, with both crushing and a shear-like cut. The different failure modes can occur due to varying load application or uneven particle distribution within the specimen. The failure between layers, that happened in one cylinder, is due to the lower bond strength between layers compared to within a layer.



(a) Crushing failure



(b) Shear failure

Figure 2.11: Pictures showing different failure modes of cylinders.

The cylinders tended to crush in the layer that was rammed last. This was confirmed by testing one of each cylinder with the last rammed layer up, and one with the last rammed layer down. The tendency can be explained by the surcharge force that compacts the bottom layers extra when ramming the layers above.

When calculating the unconfined compressive strength according to Equation 2.4, it is assumed that the failure always occurs directly below the compression plate. This might not always be the case, but it is difficult to tell exactly where the failure occurs. Hence, it is concluded that when testing the compressive strength in the test equipment, cylindrical specimens where the whole cross-section is loaded gives more reliable results.

Something noticed during the testing was that the top of the specimen was not al-

ways completely flat. This can result in unequal load distribution on the specimens, which might have caused stress concentrations. Cracks sometimes appeared before the compression plate was completely in contact with the specimen. The calculated stresses can therefore be lower than what the specimen was subjected to. The actual application area could not be estimated. The calculated stresses should however be on the safe side since the full contact area is used for the calculations, but the actual area might have been smaller. To avoid this source of error in future tests, the top surface can be polished flat before performing the test.

2.3.4 Final evaluation of test equipment

To further evaluate the test equipment, a third compression test is carried out with more samples. This time with cylindrical samples where the load is distributed over the entire cross section. According to Fabbri et al. (2022), the specimen should have a diameter between 100 to 150 mm and a diameter-to-height ratio of 1:2. Since the test equipment is unable to apply loads high enough to break dimensions of that size, the diameter is reduced to 70 mm and the height to approximately 140 mm. Figure 2.12 shows the seven test cylinders. The test was performed at Chalmers on the 8th of March.

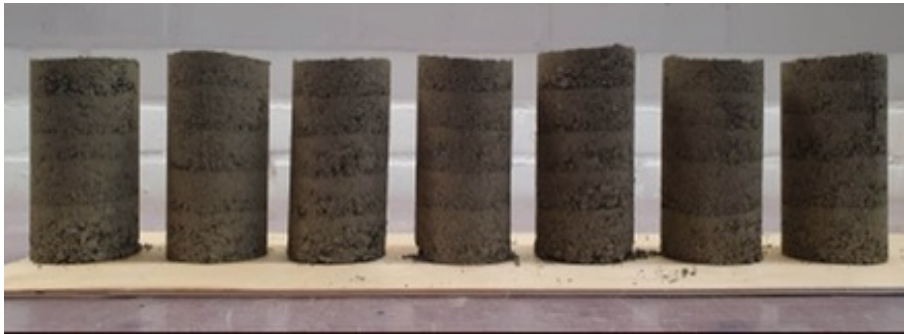


Figure 2.12: Dried specimen before polished and compression tested.

2.3.4.1 Test method

Seven rammed cylinders were left to dry at room temperature for eight days before tested. The earth mix used for all the cylinders was the same as when ramming the wall, jar test can be seen in Figure 2.4. This time, a separate steel plate was used to distribute the load over the entire specimen and the stresses were calculated according to Equation 2.2. The characteristic unconfined compressive strength of the cylinders was calculated according to Equation 2.5, using Equation 2.6 and Equation 2.7 from Appendix A in Walker et al. (2005). The result was compared to the recommended characteristic unconfined compressive strength which is a minimum of 1.0 MPa. Worth noticing is that the test is not performed exactly as described in the literature, with e.g. other drying conditions and specimen sizes.

$$f_{cu} = f_a - 1.65\sigma_{n-1} \quad (2.5)$$

$$f_a = \frac{\sum \sigma}{n} \quad (2.6)$$

$$\sigma_{n-1} = \sqrt{\frac{\sum(\sigma - f_a)^2}{n - 1}} \quad (2.7)$$

where: f_{cu} = characteristic unconfined compressive strength [Pa]
 f_a = average compressive strength [Pa]
 σ_{n-1} = standard deviation [Pa]
 σ = stress [Pa]
 n = number of specimen [-]

The strain is measured every 5 kg on the scale. The vernier caliper is placed between the supporting plates. The modulus of elasticity is calculated using Equation 2.8.

$$E = \frac{\Delta \sigma}{\Delta \varepsilon} \quad (2.8)$$

where: E = modulus of elasticity [Pa]
 σ = stress [Pa]
 ε = strain [-]

2.3.4.2 Results

The results from the compression test is presented in Table 2.6. In Figure 2.13 the measured stress-strain relation is presented and in Table 2.7 the calculated elastic modulus. The elastic modulus for respective specimen is calculated as the slope between the third and the second last measuring point. All the result data and calculations can be found in Appendix C.

Table 2.6: Failure loads for cylinders, all rammed with the same earth mix. Test 3 - 08.03.2023.

	Compression			
	P [kN]	σ [MPa]	f_a [MPa]	f_c [MPa]
Cylinder 1	7.48	1.94	1.50	1.08
Cylinder 2	6.26	1.64		
Cylinder 3	4.49	1.17		
Cylinder 4	5.01	1.30		
Cylinder 5	5.21	1.35		
Cylinder 6	5.83	1.51		
Cylinder 7	6.14	1.60		

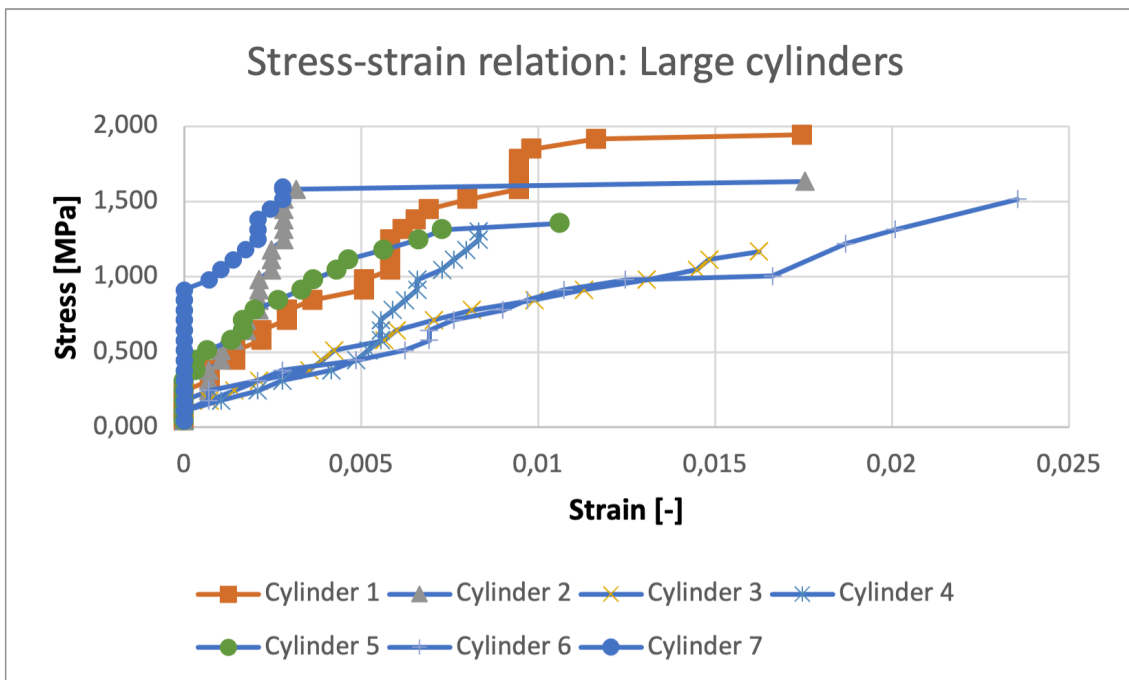


Figure 2.13: Measured stress-strain relation for all seven cylinders.

Table 2.7: Elastic modulus for the cylinders as well as the mean elastic modulus for all cylinders. Test 3 - 08.03.2023.

	Compression	
	E [MPa]	E_{mean} [MPa]
Cylinder 1	149	218
Cylinder 2	445	
Cylinder 3	66	
Cylinder 4	147	
Cylinder 5	156	
Cylinder 6	59	
Cylinder 7	505	

2.3.4.3 Discussion

As can be seen in Table 2.6, the test gave a relatively unambiguous result for the compressive strength. There are three specimens around 1.5 to 1.6 MPa, and two around 1.3 MPa. Then there are Cylinder 1 and Cylinder 3 deviating more than the others, one on the high end and one on the low end. The average compressive strength is calculated to 1.50 MPa, which is the exact limit for a one-storey building according to Keable and Keable (1996). When comparing to the construction guidelines from Walker et al. (2005), the limit of 1.0 MPa for characteristic unconfined compressive strength is reached with a calculated strength of 1.08 MPa.

The results suggests that the test equipment can give an indication of the compressive strength and its suitability if adequate number of test specimens are tested, although lab tests will be necessary to achieve exact properties.

One of the main problems with the testing is to obtain a flat enough compressive area to assure an equally distributed stress in the specimen. Although the surface was polished with sandpaper before loading, it was not completely flat. According to Walker et al. (2005), the most efficient solution would be to add a thin layer of plaster on both ends of the specimen to ensure flat compression areas. This was not possible for this test, but can be done in a lab.

The modulus of elasticity varied between the specimens, see Table 2.7. The mean value, E_{mean} , is within the expected range for rammed earth of 100-500 MPa (Walker et al., 2005). The values varied to a large extent depending on the points used for the calculations where the corresponding measuring points were used for all specimen. The third and the second last point were chosen to be the most representative for all the curves. The first three were disregarded since the plate might need some pressure to settle. Deflection just before the failure was hard to measure since the specimen collapses and therefore the last measuring point was also disregarded.

Conclusions drawn from this test are, i.a. that larger cylinders are the best geometry of specimens due to the possibility of achieving relatively uniformly rammed speci-

mens without corners affecting the stress distribution. Further, there is no need for recalculations of the effective area if the entire cylinder is loaded. To achieve a more reliable indication of the compressive strength, several cylinders rammed in a similar way and of the same earth mix, should be tested. Hence, the average compressive strength, f_a , can be compared to the limit presented by Keable and Keable (1996), as well as the characteristic unconfined compressive strength, f_{cu} , compared to the limit stated by Walker et al. (2005). These conclusions will be used when testing the earth in The Gambia. However, the stress-strain relations and modulus of elasticity is considered too time-consuming and complicated to perform in a reliable way on site.

3

Field studies

By spending eight weeks in the urban area along the west coast of the country, observations regarding the Gambian culture, weather, current built environment and existing earth constructions were made. In this chapter, the knowledge and the insights gained are presented. The considered aspects were encountered through observations and study visits as well as interactions with people in The Gambia. Ramming and compression tests of local soil mixes were performed. Further, a workshop was done which is described in Chapter 5. Cultural aspects, which are not vital to answer the research question, are presented in orange boxes. These boxes can be read if extra input regarding the country and its culture is of interest.

From getting to know the people of the country, some important cultural and local aspects are discovered. There are many different tribes and languages co-living in the country which creates an open environment. Overall, the people of The Gambia are friendly and welcoming. They are helpful and share with each other. As Salif, chef at a hotel, describes the mentality of the Gambian people: If someone goes hungry, you share your food with them.

The family is important and they often live together in a house or compound in multi-generational homes. They help each other looking after the children and take care of the household. When the parents grow older, they usually move in together with their children who take care of and provide for them.

Overall, the people in the country are poorer than people in Sweden. Money is lacking and many jobs are occasional, not providing a continuous income. The tourism industry is important for the economy and the tourism season is commonly from October to end of April. For people working within tourism, the rest of the year can consist of occasional jobs, or no work. The unstable economical situation can sometimes be seen at construction sites. The construction starts even though the money is not enough to complete the whole structure. When money runs out it is paused until there is money to continue. Finishing the construction can take months or years depending on the financial situation.

Observations have mainly taken place along the west coast of The Gambia, on the southern bank of the river. From these observations, along with interactions

with inhabitants, local builders and engineers, a perception of the current building techniques, building materials and structural design has been obtained.

3.1 Current built environment

Most buildings in the urban area are built with concrete blocks, or cement blocks as they are commonly called in The Gambia, together with concrete beams and columns. The buildings are usually plastered with cement plaster and painted. An ordinary street with houses in the urban area can be seen in Figure 3.1a.

There are also examples where tiles are used as facade material. The roof is commonly of corrugated steel sheets, or steel sheets imitating the shape of burned brick roofs. Almost all buildings, except from shops and restaurants, have a wall surrounding the property protecting from intruders.

Small shelters can also be found, usually made of corrugated steel pieces as both roof and walls. The sheets are attached to a slender wooden construction or parts of a concrete wall. In some cases ropes, stones or tires are used to keep the roof of steel or tarp in place, see Figure 3.1b.



(a) An ordinary street in the urban area.



(b) Corrugated steel roof repaired with tart and kept in place with stones.

Figure 3.1: Common constructions in The Gambia.

3.1.1 Concrete block structure

The concrete blocks are usually produced on site by mixing cement, sand and sometimes bigger aggregates with water. The mix is then cast in formworks where standard sizes are 400x200mm and 400x150mm, both with cavities in each block, see Figure 3.2a. The blocks are left to cure for a few days before mounted in the structure with cement-based mortar. To stabilize the wall, concrete columns are cast evenly spaced by leaving a gap in the block wall and attaching wooden sheets on both sides. In this way the blocks are part of the casting formwork. The beams over the openings are also made with concrete cast on site, using a similar formwork as for the columns. An example of concrete wall with column and beam over window can be seen in Figure 3.2b. The most common reinforcing method is one bar in each corner of the beam or column, together with stirrups. The floor slabs can be a cast-in-situ concrete slab or constructed by concrete blocks held up by upside down T-beams.



(a) Concrete blocks cast on site.



(b) Concrete wall built up with blocks and cast in-situ concrete pillar and beam.

Figure 3.2: Ordinary concrete construction.

The pouring of in-situ concrete on site is usually made using buckets. The buckets are filled and poured by hand, as can be seen in Figure 3.3.



Figure 3.3: Worker on concrete block wall casting a pillar.

Additionally, the picture shows what the safety at a construction site can look like. Varying levels of safety has been observed where some construction workers wear helmet while others have no safety gear at all. The man in the picture is standing on top of the wall, balancing on a concrete block. He is not wearing any safety gear when pulling up the bucket of concrete from his colleague on the ground, who refills the empty bucket with concrete.

According to a standard school design in The Gambia, published by the Ministry of Basic & Secondary Education (MoBSE), one concrete block should be able to take 2.5 MPa in compression. Most often, blocks are tested during construction to make sure the strength is sufficient. The contractor should also at any point be prepared to present blocks that can be tested by the authorities during construction. Still, the strength of most concrete blocks are not very high. The mix with mostly sand and small gravel makes them crumbly. One can crush parts of a block using only hand power, which was tested during a site visit. Many blocks are partly or fully broken during production, transportation or mounting.

There are many reasons to why concrete blocks are so widely used in The Gambia. Augustine Manneh is head of the construction department at Future in our hands The Gambia (FIOHTG). It is a non-governmental organisation (NGO), partly working with building schools around the country. He claims that one of the main reasons people use concrete blocks in The Gambia is that the curing time is only two days before they can be mounted (personal interaction, 22 of March, 2023). It is also a trusted method amongst people and the government. Highlighted from several

separate discussions with Gambians are that people are overall hesitant to changes. They prefer what is already known and want to see it with their own eyes before believing in new solutions. Jainaba T. Sarr, Director of FIOHTG, believes that to change people's and the government's perception, physical examples should be executed (personal interaction, 22 of March, 2023). Another reason for the use of concrete blocks, discovered through conversations with people in the country, is that the concrete blocks seems to represent the industrialization and the future to people. They are deemed trustworthy and a modern alternative to the traditional building methods that has been used in the country before, including earth houses.

3.1.2 Roof structure

The most common roof cover in the urban area is corrugated steel sheets, or steel sheets covered with sand or gravel, imitating roof tiles in shape, see Figure 3.4. The gravel surface is to reduce sound during rain, according to the civil engineer and constructor Mustafa (personal interaction, 19 of March, 2023). Some properties use regular burned brick tiles while some smaller shelters have tarp or other found plastics as roof cover.



Figure 3.4: Steel roof looking like tiles.

Thatched roofs is another roof cover used in The Gambia. Elephant grass is the straw most often used, which naturally grows in the country and has very long straws. Thatching is an old technique used for covering a building and it is still used on new buildings. The grass is completely dried before mounted. Thatched roofs has to be built properly to be considered watertight. There are many cases where the roofs have started leaking during the rainy season (Augustine Manneh, personal interaction, 31 of March, 2023). If the roof starts leaking it can not be fixed until rainy season is over, since there is no dried grass available at that time of year. Today one solution is to add corrugated steel sheets below the grass to reduce the risk of water leakage. The grass is then used as insulation to reduce heat as

well as sound inside the building. An example of thatched roof with steel corrugates underneath can be seen in Figure 3.5.



Figure 3.5: Thatched roof with corrugated steel underneath.

The load bearing roof structure is usually made of wood or steel when using steel sheets as roof cover. The wood is usually imported wood, or mangrove or palm tree which can be found in The Gambia (Mustafa, personal interaction, 19 of March, 2023). Imported wood is expensive. Palm tree or other wooden products of good quality from The Gambia is hard to get hold of and increasing in price. They are usually not produced in a sustainable way and is contributing to the deforestation of the country. Palm tree wood can be a durable option for a structure if the right quality is found. According to Mustafa, palm tree laths can hold for up to 50 years if they are of good quality. Steel structures are more expensive, but used when the spans are too long for a wooden structure. There are also concrete roof structures, where there is either a load bearing concrete plate as a roof, or concrete blocks together with upside down T-beams forming the roof.

Almost every property has a surrounding wall to protect from intruders as well as from flooding during rainy season. Aisha Jobe, who is working for EBG-Aid, says that neighbors can share the walls in between properties to reduce the cost of construction (personal interaction, 17 of March, 2023). The walls are usually made of concrete blocks with stabilizing columns, made of either cast-in-situ concrete or rotated concrete blocks, every third to fourth meter. The walls are plastered or left bare. On top of the walls there can be barbed wire, steel arrows or crushed glass bottles to prevent people from getting into the compound. In Figure 3.6, an ordinary street with protecting walls can be seen.



Figure 3.6: Ordinary street with protective walls.

3.2 Earth construction in The Gambia

In The Gambia many people know about earth houses, or mud houses as they are sometimes referred to in the country. In the urban areas earth houses are rarely seen, however, some earth houses are plastered and therefore hard to detect. During the field studies two entrepreneurs who are both working with compressed earth blocks (CEB) in a modern context were visited. In the following section, information about CEB as well as insights from our field studies regarding earth construction are presented.

3.2.1 Compressed earth blocks

Compressed earth blocks are blocks made of earth that are compacted under high loads in a press (Fabbri et al., 2022). The blocks can have different sizes depending on which mould is used. The press can compact either from one or two sides which affect the final density as well as the strength. A press compacting from two sides give a more uniform density and strength while a single ram press give higher density closer to the movable side. The dry density normally range between 1800-2000 kg/m³. The blocks look similar to bricks but are not burned, only left to dry in ambient temperature for circa 28 days. The earth composition of CEB is similar to rammed earth and can be stabilized using similar additives. Common stabilizers for stabilized compressed earth blocks are cement, lime or alkaline solutions which improve the mechanical properties and durability. From the field studies it was established that cement stabilizer is most common in The Gambia.

3.2.2 Construction details

Similar to rammed earth, CEB constructions are sensitive to water. Therefore a boot, coat and hat are important to protect the structure. Fake Bachata, a CEB entrepreneur focusing on eco-buildings, usually construct the foundation with a concrete beam resting on plinths to avoid settlements, which also provides a good boot, see Figure 3.7a. When asked if any capillary break is used between the concrete and CEB, the answer from Bachata is no. The CEB surface is painted with Deck Flex, a transparent surface treatment, to prevent the wall from getting algae growth.

In Bachatas project the CEB walls serve as load-bearing structure together with concrete pillars cast inside the walls. No casting formwork is needed, instead the CEB are used as lost formwork, see Figure 3.7b. Lintels are usually cast over openings and hidden behind U-shaped CEB. The blocks Bachata produces are made with either a manual press applying 15 tons or a hydraulic press applying 20 tons. In all projects visited, cement stabilizer is used to some extent. Bachata explains that in his projects, the costumer decides the amount of stabilizer and he stresses that it is the costumer that should feel safe living in the house.



(a) Boot beam as plinth.



(b) Re-bars prepared for casting concrete pillar with CEB as lost formwork.

Figure 3.7: Construction site for a CEB house.

Fake Bachata also gave a guided tour of his home which is built with CEB. There,

the lower part of the exterior wall is plastered with seashell based plaster which, according to Bachata, is an old plastering technique. Further, crushed seashells are added for aesthetic reasons. The house has a thatched roof with overhang, see Figure 3.8. The roof and its overhang is relatively steep, providing protection of the wall. In the middle of the house there is double floor height and the windows both on bottom and top floor are provided with small openings to keep the air circulating, i.e. the chimney effect is utilized in the building. A plastic film is placed underneath the whole foundation to provide protection from termites.



Figure 3.8: Picture of Fake Bachata's house made from CEB with thatched roof and seashell plaster.

CEB walls can either be load bearing or non-load bearing. At Mbolo Association in Fandema, examples of earth structures built with CEB as non-load bearing structure are found. The CEB wall structure keeps the indoor climate from fluctuating while the load bearing structure consists of concrete beams and columns. Hence, the load bearing structure is not as sensitive to water.

3.2.3 Rammed earth in The Gambia

There are rammed earth buildings in The Gambia, though they are quite rare in the urban area. The entrepreneur Adama Samba, is working with rammed earth in a modern context in the greater Banjul area. He works with a modern re-usable formwork constructing various buildings. A study visit to one of his construction sites was planned, but unfortunately cancelled.

A recent example of a rammed earth construction project, run by Banko Foundation, is found in Karsi Kunda. Karsi Kunda is a village in the rural area of eastern Gambia (Erika Alatalo, 2019). In the project, challenges were faced regarding creating a strong enough formwork, since strong and affordable wood were hard to find. This resulted in weak spots in the rammed earth wall. In Karsi Kunda they also experienced challenges with keeping the wall dry during construction since they were constructing during the rainy season. Using rammed earth was therefore deemed unsuitable in the context of rural Gambia. Worth noticing is that only local materials and knowledge were used.

3.2.4 Perception of earth building in The Gambia

In The Gambia, building with earth is considered an old method belonging to the past. It is perceived unsafe and undurable, especially due to the rainy seasons and flooding. Some people say that they want to live in a house made of earth because of the cool temperature during warm days. However, many people do still not trust the building technique together with rain and water since there are many examples that have been destroyed.

The government of The Gambia is, as earlier mentioned, slightly more hesitant to earth buildings, according to FIOHTG (personal interaction, 22 of March, 2023). There are standard solutions for buildings constructed with concrete blocks (Augustine Manneh, personal interaction, 31 of March, 2023). When applying for a building permit for a structure that is not following the standard solutions, a presentation of the concept is needed at the Department of Physical Planning in The Gambia, to show that the intended solution is feasible. This can be done by e.g. engineering calculations, lab tests and a structural design. For example, FIOHTG have constructed two buildings with CEB and for these permits, the design was presented together with lab tests of the earth blocks.

3.2.5 Economy

Overall, the material cost for an earth building in The Gambia should be cheaper than for a concrete block house with imported cement. The construction technique, especially for rammed earth, requires more labour than a concrete house, which increases the cost. The knowledge of earth construction is not as available as concrete construction, which also influences the cost. Therefore, the construction of earth houses is not as cheap as expected. Two local earth entrepreneurs, Alpha Omar Jallow who is working with CEB and Adama Samba who is working with rammed earth, both claims that earth constructions are 15% cheaper than concrete constructions in The Gambia. The CEB entrepreneur Fake Bachata, claims that an earth building saves money in the long run from reducing the cost of electricity for air conditioning and fans that are commonly used in a concrete house (personal interaction, 29 of March, 2023). He also claims that there are plenty of savings from not repainting the plaster every third year, which he says is needed for a plastered building. A CEB facade treated with Deck Flex does not need maintenance for a

long time if produced correctly, according to Bachata.

3.3 Weather in The Gambia

The rainy season is a hot period with heavy rain that can go on for days. According to Salif, who is working as a chef, the rain can go on non-stop for more than 24 hours, with high intensity the whole time (personal interaction, 27 of March, 2023). The rain can cause severe flooding and destroy roads and properties. There are ways where the stream usually go, however, when new properties and new protecting walls are built, the way of the water can change and go into someones property. The water can be several meters above usual level and destroy entire compounds. Salif also said that to protect a property from water during rainy season, the most important thing is to create a sloping ground of the property, to provide good drainage (personal interaction, 20 of April, 2023). Salif has been noticing how the climate is changing and that the temperature is getting warmer earlier in the year (personal interaction, 15 of March, 2023). FIOHTG also mentions that the climate change is observable, especially at the northern banks of the river. Sandstorms from Sahara is another natural event that occur occasionally (Aisha Jobe, personal interaction, 19 of April, 2023).

3.4 School

In The Gambia, school is in theory free if attending a public school. However, the students must buy all the supplies and books needed for the education, i.e. in practice it can still become a considerable cost (Aisha Jobe, personal interaction, 19 of April, 2023).

The private schools or schools run by NGOs usually have a rather expensive tuition. The overall opinion of the people is that the private schools have better education and better teachers compared to public schools. It is usually a matter of money that decides which school a child attends, according to Jao, teacher in a village pre-school (personal interaction, 17 of March, 2023).

The schools in The Gambia have a longer summer break, usually around July to September, which coincides with the rainy season. There can be long distances for children to walk or get to school, especially for higher education or when the school in the area does not offer all subjects (UNDP & The Republic of The Gambia, 2020). Safi, mother of four kids living in Brufut, looks forward to the new school being built in the area so that the children do not have to walk that far to school (personal interaction, 17 of March, 2023).

According to FIOHTG, there are many schools, especially in the rural areas of the country, where the classroom can be a shelter of weaved mats of grass or palm leaves. There are standard solutions for school buildings, published by MoBSE, where con-

3. Field studies

crete blocks are the load bearing structure. This is most common when producing new schools, according to Manneh (personal interaction, 17 of March, 2023). If a school is designed following these standards, there is no need to apply for a building permit at the Department of Physical Planning (Augustine Manneh, personal interaction, 31 of March, 2023). FIOHTG mainly uses the standard designs with concrete blocks since that is what the donors asks for. The donors provide funding and ask for schools in concrete blocks since it is considered an easier building method, less expensive and less time-consuming.

One private school and one public school were visited in The Gambia. The private school was built with CEB and the visit took place during a lecture break. During the break, the doors where open and kids walked freely in and out of the classroom, see Figure 3.9a. This results in a high air exchange rate hence the temperature difference between indoors and outdoors was reduced. The school had windows that were covered with blankets on the inside. This keeps the sun from heating up the classroom but results in dim light. The roof overhang provide shaded areas around the building. Inside the classrooms, there were benches and whiteboards and noticeboards on the walls, see an example of classroom in Figure 3.9b. In a classroom for younger kids in nursery school, there were some posters and arts and crafts designs hanging on the wall.



(a) Roof overhang providing shade while the doors to the classrooms are open.



(b) Classroom interior.

Figure 3.9: Study visit at Mbolo Association, school made of CEB.

The second school visited was to the public school Sanchaba Sulay Jobe Lower Basic School, see Figure 3.10. It is a big school with 35 classrooms and 3 000 students coming to the school in two shifts, morning shift and afternoon shift (Fatoumatta Kassama, personal interaction, 2 of May, 2023). Most of the buildings are one storey buildings but two-storey buildings exists at the school. The load bearing structure is concrete blocks with steel trusses and wood laths carrying the corrugated steel roof. The walls are either perforated or provided with openings covered with burglar bars to ventilate the building, see Figure 3.10a. The greater parts of the school is not electrified which means the daylight passing through the openings is the only light inside the classrooms, and there are no electrical ventilation.



(a) The class room walls are perforated to provide daylight and natural ventilation.



(b) Children playing on the school yard during break.

Figure 3.10: Study visit at a Sanchaba Sulay Jobe LBS.

During the school visit to Sanchaba Sulay Jobe Lower Basic School, the deputy headmistress Fatoumatta Kassama expressed a need of raising the fence around the school to prevent intruders during nighttime, which is a weekly recurrent problem (personal interaction, 2 of May, 2023). When discussing weather and how it affects the teaching, she explained that the heat is a problem. Since the school is not electrified there are no fans, only natural ventilation. She also expressed that there are parts of the year where it is considered cold in the class rooms since there are no windows to close. Further, the wind itself and the fact that the wind brings dust inside the classrooms was considered a problem. Further, the heavy rains occurring makes it noisy inside the classroom and disables the students to hear the teacher

properly.

Some things observed on the schoolyard during the break was that kids play football, sometimes against the walls of the school. There are also other games played against the walls, as well as students seeking shadow under the roof overhang or trees. There are water taps on the school ground for kids to drink water or cool down. What could also be observed in the classrooms was that there were posters on the walls and a blackboard in most classrooms. One could also see that some walls had marks from furniture and marks from kids scribbling on the wall.

3.5 Physical explorations

Ramming of large cylinders and compression tests of earth from The Gambia was performed to compare different earth mixes. Firstly, an earth mix bought from an entrepreneur working with rammed earth was rammed and compression tested. Due to low compression strength, a second mix was collected from a road construction and tested with the same procedure. The two earth mixes can be seen in Figure 3.11.



(a) earth bought from a rammed earth entrepreneur.



(b) earth collected from a road construction.

Figure 3.11: Two earth mixes tested in The Gambia.

3.5.1 Ramming with Gambian earth

Firstly, eight large cylinders were rammed using an already mixed, unstabilized, earth from the rammed earth builder Adama Samba. The mix was dry when received, and thereafter mixed with water to achieve a good moisture content for ramming. The earth was solely consisting of fine particles with no gravel or larger particles, see Figure 3.11a.

The mixing was done by hand by continuously adding small amounts of earth and water and mixed in a bucket. By using this technique, a mix was received without big lumps. Several ball drop tests were performed to certify that the moisture content was suitable for ramming. The earth was considered a bit too sandy from the ball drop test, but with no extra clay to add, the ramming was proceeded with the mix.

The ramming was done in the same cylindrical form as was used in Sweden. What could be found at site was used as rammers, in this case an empty glass bottle and a wooden stick together with a hammer. The cylinders were rammed in five layers of equal thickness to have similar conditions as for the cylinders rammed in Sweden.

The surfaces of the rammed cylinders looked even and homogeneous with slightly visible layering in a few cylinders, see the left cylinder in Figure 3.12. The top surface of the cylinders were smoothed by hand to avoid uneven loading to the greatest extent.



Figure 3.12: Rammed samples. Left: Bought earth from rammed earth entrepreneur. Right: earth from road construction.

A second ramming was performed with a similar method and similar tools as the first time described above. Although this time the earth was taken from a road construction site. The earth was more red in color and contained larger particle sizes, see Figure 3.11b. Stones larger than one centimeter were removed before ramming. After mixed with water, the earth felt like it contained more clay than the previous earth. It was easier to obtain a good ball drop test result than for the previous mix. Clearly visible layers could be seen in the cylinders, see the right cylinder in Figure 3.12.

A third mix was rammed containing the bought earth mix from the entrepreneur with 5% cement added. The ramming procedure and the result was similar to the samples rammed first.

3.5.2 Jar test

A jar test was performed on the bought ramming earth, where the result did not show any visible layers. The particle sizes were very similar throughout the earth and no conclusion about the clay content was drawn. The jar test of the earth from the road construction showed a clay content of approximately 15%. Both the tests were left to settle for several days.

3.5.3 Compression tests

The compression tests of the eight cylinders rammed with the bought earth was performed after eight days of drying. The same test equipment as in Sweden was used. To achieve a good test setup, parts of concrete blocks and crushed tiles found on the street were used as build-up and load distributor. The test set up can be seen in Figure 3.13, with the tile distributing the load over the full cross section. The stresses were calculated according to Equation 2.2 and the characteristic unconfined compression strength according to Equation 2.5. The results can be seen in Table 3.1 and the full data set in Appendix D.



Figure 3.13: Test set-up in The Gambia.

Table 3.1: Failure loads for cylinders with bought earth, cylinder number 2 disregarded.

	Compression			
	P [kN]	σ [MPa]	f_a [MPa]	f_c [MPa]
Cylinder 1	2.57	0.67	0.91	0.66
Cylinder 2	-	-		
Cylinder 3	4.01	1.04		
Cylinder 4	3.81	0.99		
Cylinder 5	3.70	0.96		
Cylinder 6	4.01	1.04		
Cylinder 7	2.83	0.74		
Cylinder 8	3.50	0.91		

Cylinder number 2 is disregarded in the evaluation due to the load distributing tile on top breaking during loading. The break caused an edge of the tile being pushed towards the cylinder, causing uneven load distribution and cracking directly beneath the edge, see Figure 3.14.



Figure 3.14: Tile broke during compression test, therefore the specimen result was disregarded.

With the same set-up and procedure as previously described, the compressive strength of the cylinders rammed with road construction earth was tested. The results can be found in Table 3.2.

Table 3.2: Failure loads for cylinders rammed with road construction earth and eight days of drying.

	Compression			
	P [kN]	σ [MPa]	f_a [MPa]	f_c [MPa]
Cylinder 1	1.54	0.4	0.54	0.24
Cylinder 2	1.85	0.48		
Cylinder 3	3.29	0.86		
Cylinder 4	2.06	0.53		
Cylinder 5	1.70	0.44		

For the cylinders with 5% cement added, the compressive strength results can be found in Table 3.3.

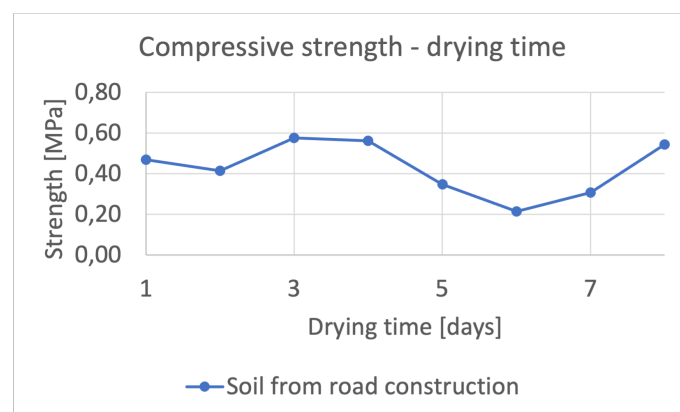
Table 3.3: Failure loads for cylinders rammed with bought earth and 5% added cement.

	Compression			
	P [kN]	σ [MPa]	f_a [MPa]	f_c [MPa]
Cylinder 1	3.29	0.86	0.91	0.55
Cylinder 2	4.12	1.07		
Cylinder 3	2.83	0.74		
Cylinder 4	3.24	0.84		
Cylinder 5	4.89	1.27		
Cylinder 6	2.68	0.70		

As an additional test, the influence of the drying time on the compressive strength is evaluated. One cylinder was tested each day after ramming, until eight days of drying was obtained. The cylinders were rammed with road construction earth and the results can be seen in Table 3.4. The relation between compressive strength and drying time can also be seen in Figure 3.15.

Table 3.4: Failure loads for cylinders with varying drying time, rammed with the road construction earth.

	Compression			
	P [kN]	σ [MPa]	f_a [MPa]	f_c [MPa]
Day 1	1.8	0.47	0.43	0.21
Day 2	1.6	0.41		
Day 3	2.21	0.57		
Day 4	2.16	0.56		
Day 5	1.34	0.35		
Day 6	0.82	0.21		
Day 7	1.18	0.31		
Day 8: average	-	0.54		

**Figure 3.15:** Relation between compressive strength and drying time

The cylinders for comparing the different earth mixes were left to dry for eight days, same as for the cylinders in Sweden. The climate is warmer and drier in The Gambia compared to Sweden, which can affect the drying rate. However, the cylinders were left to dry indoors in both Sweden and The Gambia, which reduces the difference. The indoor temperature in The Gambia is commonly warmer than in Sweden, but since there is no direct sunlight, it is cooler indoors than outdoors.

For the cylinders made from the entrepreneur's earth, they usually failed in the top half of the cylinder, most often starting with crushing at the very top. The failure modes indicate that there is little bond between particles, which could be a result from low clay content. Only a few specimens reaches above 1 MPa, which is regarded low compressive strength for rammed earth. The earth was said to be already mixed. It felt rather sandy, which was also indicated in the jar test. The clay content is unknown and assumed rather low taking the previous aspects as well as the failure modes into account. The specimens tested had to be transported from one location to another. During transportation they were placed together in a bucket and transported on a bumpy road, which can have caused defects on the cylinders. This might have affected the results of the compression tests.

The specimens with road construction earth showed a low compressive strength in general even though the jar test and ball drop test indicated a good earth mix. The results of the compressive strengths were not diverging much except from Cylinder 3, which was significantly stronger. The failure modes were generally shear failures which might be a result from uneven loading or larger particles present in the mix.

The earth containing 5% cement received a surprisingly low strength compared to the unstabilized mix of the same earth. The failures did however appear more ductile, with visible cracks and crushing before failing. The failure modes were shifting between crushing and shear failures. One specimen reached a significantly higher strength of 1.27 MPa compared to the others, followed by one of 1.07 MPa, see Table 3.3. The average compression strength is the same with and without added cement, which can be due to low water content. A too low water content results in the cement not reacting. Cement is usually added to achieve higher strength of the earth. However, in this test the average compressive strength is the same, while the characteristic strength is lower than for the unstabilized earth, due to higher standard deviation.

When comparing the three tested mixes, the bought mix show the best results, despite the fact that it felt sandy when ramming. The road construction earth, which felt very promising when ramming, turned out to be the least strong mix. The strength of all three mixes are rather low, both compared to compressive strength ranges in literature, as well as compared to the Swedish test results.

An additional investigation was done with the earth mix from a CEB. Old CEBs were crushed and mixed with water to see if the earth could be rammed and compression tested. The earth was deemed too sandy to ram, when mixing and performing

the ball drop test. A jar test was performed which showed a large amount of fine particles. The reason for the sandy feeling, despite the large fraction of fine particles, could be explained by the fact that the mix contained cement that had already reacted. For comparison, a dried road construction cylinder without cement was crushed and moisturised. The mixed earth was deemed rammable after performing a ball drop test. This test was done to see if earth from a cement stabilized CEB could be reused in a rammed earth structure without changing the mix.

The test of the influence of drying time shows varying results in strength. It is difficult to draw any conclusions from it, since there is no clear relation between strength and drying time in the test results. The main source of error is that only one specimen of each drying time was tested. To get a more reliable result, several cylinders should be tested for each drying period.

Based on the results from the performed tests, earth with higher compressive strength must be found for ramming a school. As previously said in Section 2.3.4.3, the test equipment only gives an indication of the compressive strength. Therefore, more accurate lab tests are advised to verify if the earth is suitable for ramming.

4

Conceptual design

In this chapter, a conceptual design of the superstructure of a two-storey school building is presented. Structural challenges and solutions are discussed for a rammed earth school in a Gambian context. The challenges were found during the pre-study and the field studies. Common solutions to the challenges are presented, evaluated, and thereafter adapted to the Gambian context as well as the school context. Further, these adapted alternatives are evaluated and the most suitable alternative is chosen. The challenges and their solutions are presented in figures where each layer represents one evaluation. A conceptual representation of a figure can be seen in Figure 4.1. In Chapter 5, a prototype of a possible floor slab as well as an implementation of the slab solution is presented.

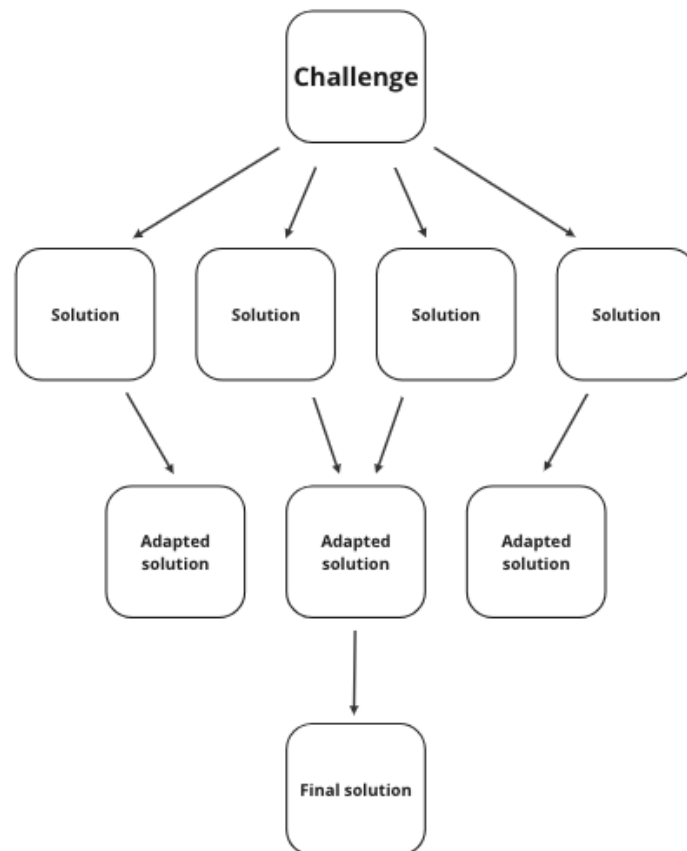


Figure 4.1: General representation of a challenge and its common and adapted solutions

4.1 Roof

The roof is one of the most expensive parts of a building in The Gambia, according to Augustine Manneh (personal interaction, 22 of March, 2023). The roof is directly facing the sun and precipitation which sets high demands on the roof cover and structure. The roof should protect the structure, especially the earth walls, from rain. It should also insulate towards heat from the sun and dampen the sound of rain. One difficulty regarding the roof in a rammed earth structure is to anchor it properly to handle lifting forces from wind. See the common and adapted roof solutions in Figure 4.2.

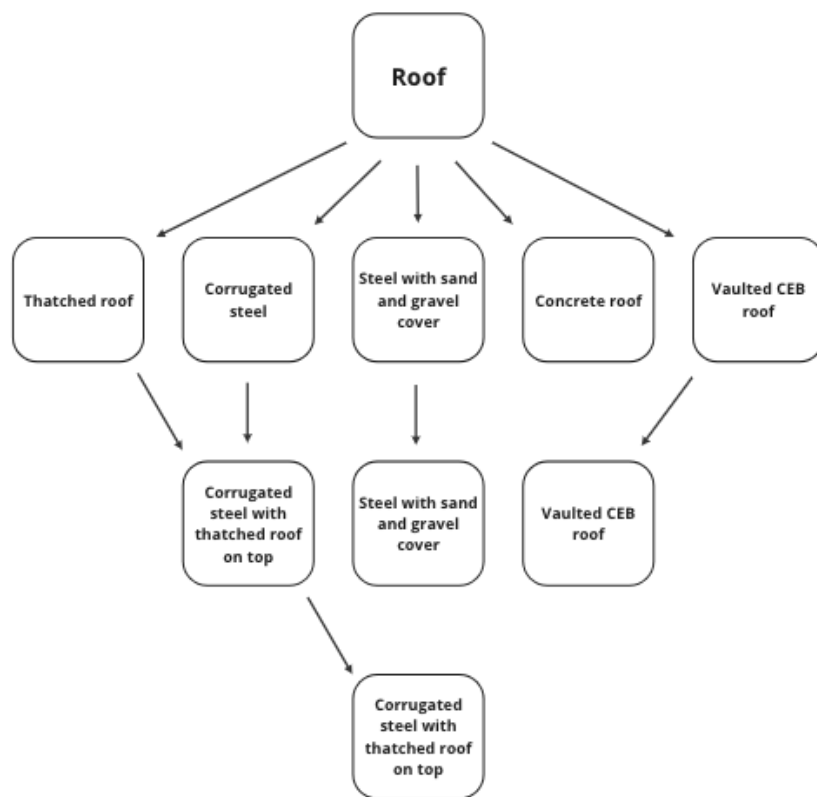


Figure 4.2: Common and adapted solutions for roof construction.

4.1.1 Common solutions

There is no standard roof structure related to rammed earth, while there are some common roof structures used in The Gambia. A rather old, but still present roof technique is thatched roof. The most common roof cover in the urban areas of The Gambia today is corrugated steel roof or steel sheets covered with sand and gravel. Flat roofs made of concrete are also seen. Further, there are CEB entrepreneurs, like Alpha Omar Jallow, who constructs vaulted roof structures and domes made from CEB.

4.1.2 Adaptations

In the school context, a roof of corrugated steel sheets is not considered a good option due to the heat it transfers into the building during the day when students are there. It is also not considered suitable due to the loud sound it produces during raining, which can disturb the education. The gravel covered steel sheets is an option with less noise and less heat transfer and widely used and available in The Gambia. The need of maintenance is not very high and the structure is lightweight. Thatched roof has good insulating capacity both for heat and sound but may be hard to maintain if damaged during the rainy season. Therefore, a modern adjustment made to this roof construction is adding steel sheets below the grass to verify that the roof is watertight and can resist the heavy rainfalls. Concrete roof is not considered a good alternative since that will increase the cement usage, it requires large amount of formwork and it should be treated to not transfer moisture into the earth walls. A vaulted roof construction using CEB could be an alternative heavy enough to resist the uplifting wind forces and have similar thermal properties as the walls, which is beneficial in the Gambian climate.

4.1.3 Final choice

The roof solution that is deemed the most suitable in this context is the thatched roof with corrugated steel sheets below. The steel sheets makes the roof watertight and protects the earth walls from water, while the grass on top reduces the heat gain from the roof and reduces the sound when raining. It might require more maintenance than steel sheets with gravel on top, but the straw is considered even better from the sound and heat aspect. Though, since there are steel sheets below the grass, the maintenance of the grass is not as crucial for the structure as if it was only a thatched roof. The grass should be treated with fire retardant.

In this context a vaulted roof of CEB is not considered the best solution, in combination with rammed earth walls, due to the need of roof overhang to protect the walls. To protect from water penetrating the walls, a roof overhang is an efficient solution. Another solution is to have an edge cover at the top of the wall, only covering the end, and protect the rest of the wall with a coating, e.g. Deck Flex. This is however not considered a good solution in this context since a roof overhang provides the school with shade around the classroom, both reducing the temperature inside the classrooms as well as providing shadowed and rain-protected areas for the children on the school ground. If doing a vaulted roof, the vault will end on the walls, resulting in the need of a separate roof structure to provide the roof overhang over the wall. If a separate structure is to be attached, the connection between these two must be very carefully designed and executed to assure no water can leak and go along the wall, causing loss in bearing capacity of the earth wall. The roof itself must also be entirely waterproof, using coating or similar. If water enters a CEB roof structure, the bearing capacity can be reduced significantly, and in worst case result in collapse of the whole roof, since the entire vault is needed to bear itself. The thatched roof with underlying corrugated steel sheets is therefore chosen as it is considered less risky and easier to execute in a watertight way than a

CEB vault. The roof is held up by steel trusses and steel or wooden laths depending on the length of the spans. The trusses are chosen to be steel to avoid potential termite attacks.

The uplifting forces from wind acting on the roof cause tensile stresses that must be taken care of. Since the decided roof type is rather lightweight and rammed earth is weak in tension, the solution where the roof is attached directly into the rammed wall by ramming in wire and nails, is disregarded. Instead, using a concrete ring beam as counterweight is deemed the simplest solution for attaching the roof and its overhang to the wall. The ring beam is cast on top of the rammed wall and the roof attached directly to the ring beam. This is a simpler solution production-wise, compared to an alternative of attaching the overhang to the foundation by columns. Even though that solution reduces the tensile stresses in the wall, the weight of the ring beam together with the roof is deemed enough to hold down the roof without the more complex solution of attaching it to the foundation.

4.2 Openings

Openings in the school building should provide the school with sufficient daylight and ventilation. Meanwhile, the openings are important to achieve a pleasant indoor temperature and utilize the heat capacity in rammed earth. Further, the openings has to be designed in a structurally efficient way for rammed earth, see Figure 4.3.

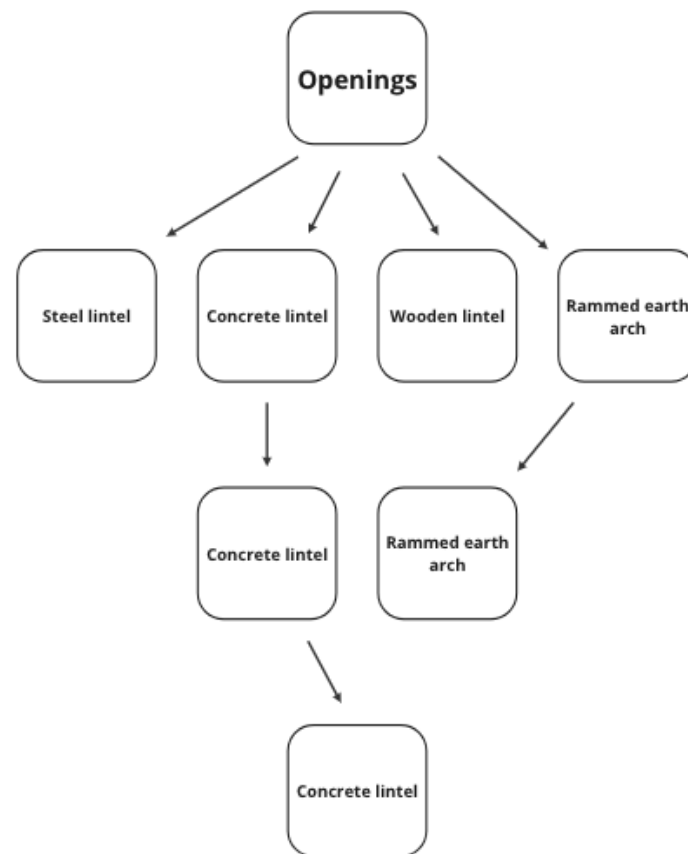


Figure 4.3: Common and adapted solutions for openings.

4.2.1 Common solutions

Common solutions when constructing openings in rammed earth walls are to add a lintel made of steel, concrete, wood or another material with sufficient bending strength. Another common solution is to shape an arch, which only uses compressive forces.

4.2.2 Adaptations

In The Gambia, reinforced concrete lintels are commonly seen and therefore an easy and accessible solution. Constructing a rammed earth arch is also a possible solution. Wooden and steel lintels are disregarded since they are harder to get hold of and wood can be attacked by termites.

4.2.3 Final choice

Concrete lintels are considered the best solution, since that is a common method overall in The Gambia. It does not require complex vaulted formwork and allow rectangular openings which makes it easier to install glass windows. Glass windows, compared to burglar bars only, would allow the teachers to decide whether they want

to ventilate more or less and in that way control the indoor temperature. Being able to close the windows also reduces the dust brought into the classroom by the wind.

4.3 Boot

The heavy rain during rainy seasons in The Gambia can cause flooding and have devastating effects on structures. It occurs that houses are water-filled and destroyed if the structure is not designed properly. Since rammed earth is sensitive to water a proper boot and drainage system is important. Bad examples of water protection has unfortunately caused a scepticism towards building with earth. Finding a suitable solution to this challenge is therefore of great importance. The alternative boot solutions are displayed in Figure 4.4. The drainage on the site is assumed adequate in all solutions.

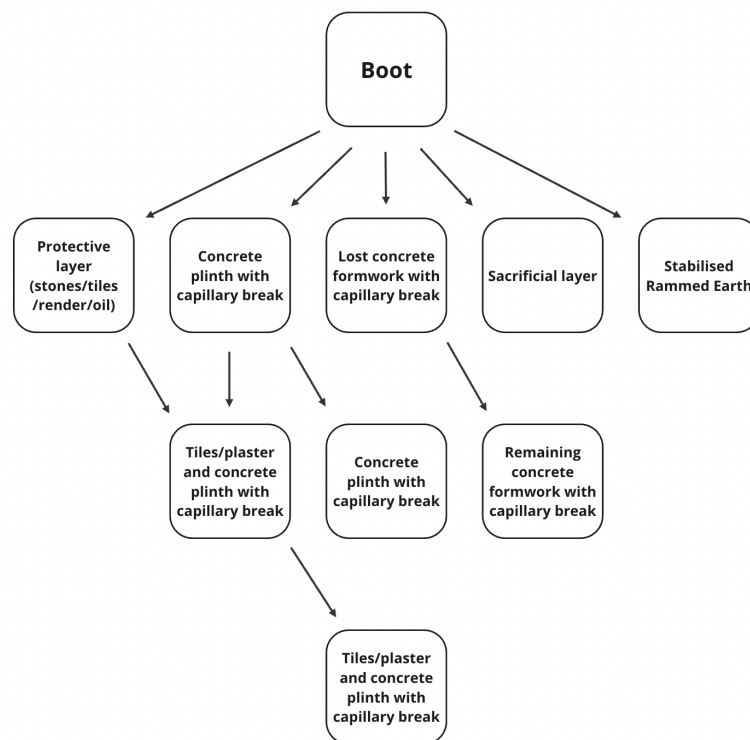


Figure 4.4: Common and adapted solutions for boot construction.

4.3.1 Common solutions

Common solutions suggested in guidelines are to provide the lower part of the structure with a protective layer i.e. stone, tiles, render, or oil. This mainly provides a water-repellent layer that protects the structure from splash-backs. Another solution is to elevate the rammed earth structure on a concrete plinth to allow for standing water around the building without risking the rammed earth structure to collapse. Similarly, a concrete beam can be cast and used as lost formwork when ramming. Both the solutions including concrete should be provided with capillary

break between the concrete and rammed earth. Further, a sacrificial layer of earth can be added to the wall that is maintained when damaged, alternatively the lower part of the wall can be built with stabilized rammed earth.

4.3.2 Adaptations

Due to the potential flooding in The Gambia, which can cause standing water both indoors and around the buildings, a protective layer is not considered a good enough solution on its own. It is challenging to make a protective layer 100% watertight and it would therefore not be sufficient in the Gambian context. The same principle applies for stabilized rammed earth. Although, a protective layer can be combined with a concrete plinth. The concrete plinth should be high enough to protect against potential standing water. As a reference, The African Standard for countries in southern Africa, SADCSTAN (2014), says that if the precipitation is above 1 000 mm per year, the floor levels should be at least 300 mm above ground level. The remaining height subjected to splash-backs should be covered with a protective layer. Suitable protective layers in a Gambian context would be tiles or cement-based plaster since they are well-known techniques. Alternatively, a plaster based on a seashell powder can be utilized. Concrete plinth or concrete formwork can be sufficient solutions, as long as the height is adapted to the risk of flooding in the neighbourhood and possible splash-backs.

Regardless of the solution chosen, the interior floor should be raised to prevent water from entering the building and the surrounding ground should have a sufficient drainage system. Further, the building should be protected from termites by using termite treatment underneath and around the building.

4.3.3 Final choice

The solution deemed most suitable is to build a concrete plinth high enough to protect against standing water. If the height of the concrete plinth is not enough to protect against splash-backs, the structure should be complemented with a protective layer, preferably seashell-based plaster to reduce the cement usage. The protective layer will also be beneficial for protecting the wall from kids playing. The interface between the concrete plinth and the rammed earth should be provided with a capillary break, e.g. bitumen coating. Through this combination, the height of the plinth can be reduced hence some cement is saved. The interior floor should always be elevated but below the concrete plinth in case there is ever standing water indoors or if the school is to wash the floors with water. According to Walker et al. (2005) the upstand should be minimum 100 mm.

4.4 Erosion

Erosion of a rammed earth wall is always a challenge. However, in this context it is especially important since there is heavy rain, wind, sandstorms as well as kids being active around the school, e.g. playing football against the wall and students

seeking shadow along it. Additionally, marks from furniture and things written on the the wall could be seen indoors. This causes a higher erosion rate and the erosion should be handled both indoors and outdoors to make sure the structural capacity is good enough and works practically in a school context, see Figure 4.5.

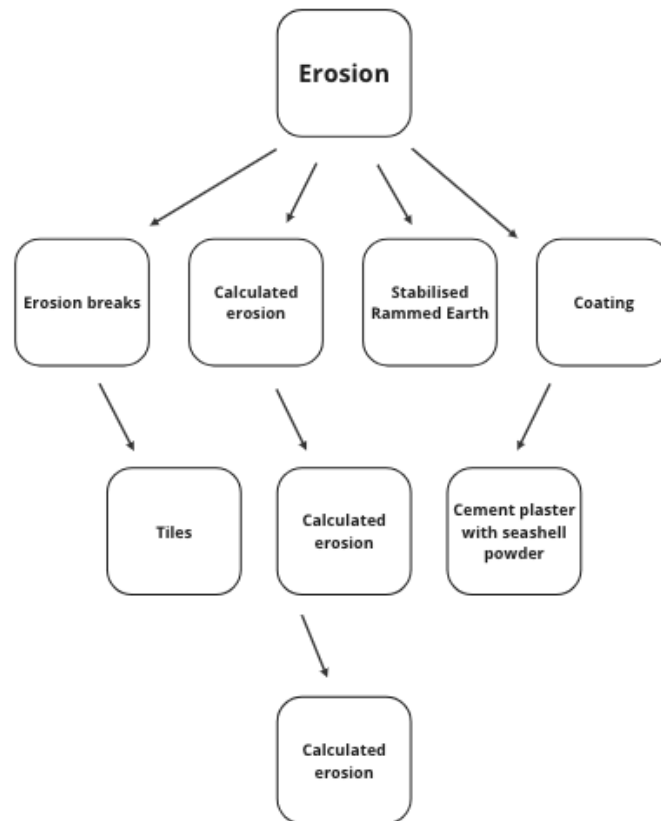


Figure 4.5: Common and adapted solutions for erosion.

4.4.1 Common solutions

Some alternatives to handle erosion in rammed earth structures are to add erosion breaks or use calculated erosion by making the wall thicker. Other solutions are to use stabilizers in the earth or to add a protective coating to prevent erosion.

4.4.2 Adaptations

Erosion breaks could be created using tiles. Stabilized rammed earth is not considered the best option since that would require a large amount of cement as well as losing many of the good qualities of earth. The recommended calculated erosion according to Erden (2022) is to add 2-3 cm extra to the wall. Due to the high activity at a school, it is deemed necessary to increase the calculated erosion. Cement based plaster is one coating alternative. Some of the cement can be replaced with seashell powder to reduce the total amount of cement. Lime based plaster is also

an alternative. When using a coating one should be aware of the reduced vapor permeability and make sure that the wall can dry out.

4.4.3 Final choice

The final solution for the exterior walls of the school is proposed to be calculated erosion. As mentioned in the adaptations, the added layer should take outdoor school activities as well as sandstorms into account. By using calculated erosion the wall keeps its vapour permeability and breathability compared to if coated. One possible negative aspect of this solution is that the erosion will be visible from the outside. It could therefore increase the already negative picture of rammed earth in The Gambia, since the degradation of earth will be on display. However, the positive aspects of making the earth visible and showing that it is possible to build a school with earth is deemed more favourable for the spread of earth construction than hiding the earth behind a plaster. Erosion breaks are an alternative, but it is deemed more costly and not sufficient to stand up to the sandstorms and activity of children. A calculated erosion of five centimeters is deemed suitable on the exterior walls on ground level. Further, less calculated erosion is deemed to be needed on the exterior wall on the second floor, since the roof overhang protects the upper part of the wall better than the lower part. Moreover, there are no children playing or touching the exterior wall on the second floor.

On the inside, it is also considered good to leave the wall without surface treatment to keep the good air quality of earth walls. It is important to let the wall dry sufficiently and brush off all the loose material before starting any school activity in the building. One centimeter of calculated erosion is deemed enough handling the indoor activities affecting the wall. The particles falling from the wall is deemed to not be a problem, since there is always sand indoors in The Gambia due to the sandy roads and the sand coming with the wind. Thus, it is preferable to have a floor that is easy to clean, so that any dust from the wall can be swept up. If no dust coming from the walls into the classrooms is accepted, plastering with cement and seashell plaster would most likely be the easiest solution in this context. By only coating one side of the wall, the wall can still dry out when moist.

4.5 Rammed earth wall

The wall is the main vertical load-carrying element in the structure and therefore utterly important. The structural properties of the wall depends mainly on the earth. From the compression tests performed in the Gambia, the compressive strength is poor, see Section 3.5.3, compared to the advised compressive strength in literature as well as the results with Swedish earth. According to Keable and Keable (1996), a compression strength of 1.5 MPa is enough for one-storey buildings and 2.0 MPa for two-storey buildings. It is therefore recommended to find an earth, stabilized or unstabilized, that reaches 2 MPa, which is what is assumed as the earth capacity in the following Chapter 5.

4. Conceptual design

When designing one of the school walls with a wall height of 2.5 m, the slenderness is the deciding factor for the wall thickness. Following the limit in SADCSTAN (2014), the ratio 1:8 is chosen to be conservative, which results in a minimal wall thickness of 320 mm. The decided calculated erosion is thereafter added to the wall thickness, see Section 4.4.3, resulting in a wall thickness of 350 mm for the upper wall. For the lower wall, the increased calculated erosion results in a wall thickness of 380 mm.

The walls needs to be horizontally stable, which can be achieved using the interior walls. If there are unbraced walls longer than nine meter, concrete columns within the rammed earth wall can be added to stabilize (SADCSTAN, 2014).

What needs to be considered during construction is that the ramming of the walls is done during the dry season. It must also be ensured that before rainy season comes, there is sufficient roof or other protection of the wall to prevent rain from destroying the wall. Making sure that the formwork is placed completely vertical and in line with the rest of the rammed wall is also important to avoid skewed walls.

5

Prototype of vaulted floor slab

During the field studies, a prototype of a CEB vault slab was designed and built in collaboration with a local builder in The Gambia. The prototype was constructed during a workshop where the design and building process were evaluated. The workshop was performed partly to test if the vaulted slab could be a suitable solution for slabs in the local context. It was also performed to gain deeper understanding of building processes in The Gambia. The findings from the workshop are presented in this chapter together with a description of how this kind of floor system could be implemented in a rammed earth school building.

The workshop was planned and executed in collaboration with the constructor Alpha Omar Jallow, who runs the company Earthwork Construction, and Simon Rustas. Jallow has been working with CEB for about 20 years and has several ongoing projects in The Gambia. Jallow is specialized in working with vaults and domes, i.a. as roof structures. He showed an interest in collaborating in a workshop on vaulted floor slabs constructed with CEB.

According to FIOHTG, the most expensive parts in a multi-storey building is the slab and roof (personal interaction, 22 of March, 2023). Material cost and cement usage can potentially be reduced by using earth as load bearing slab structure instead of concrete, which is the standard solution in The Gambia. A vaulted shape allows for compression only which is suitable when building with earth, which has low tensile strength.

The compressed earth blocks that Jallow produces have a compressive strength between 3.5 and 7 MPa depending on the amount of cement added. Jallow claims that 7 MPa is achieved when 10% cement is added. The density of the blocks were tested by measuring and weighting three blocks of different sizes, resulting in a mean density of 2013 kg/m³.

5.1 Vaulted floor system

A vaulted floor system is designed to act in pure compression by giving the load-bearing structure a funicular shape (Block et al., 2010). A vault is stable if the load is limited to uniformly distributed loads but vulnerable to asymmetric loading. Asymmetric loading can cause hinges where the thrust line leaves the material and the vault collapses. Therefore, it is of great importance to provide the vault with a

stabilizing structure handling asymmetric loading, especially point loads applied in the quarter point.

There are different solutions to make the vault stable for point loads. One solution is to add weight to the structure which makes a point load negligible (Block et al., 2010). However, this solution increases the stress within the vault structure as well as the reaction forces in the supports. Another solution is to add stiffening walls, also called rib stiffeners, along the vault to increase the structural depth and give the asymmetric load an alternative load path. Further, the structure can be stabilized through corrugations or double curvature which enables the load to find different paths within the structure.

5.2 Initial prototype design

The prototype was designed in collaboration with Rustas and Jallow. It is inspired by the vault built by i.a. Philippe Block in Addis Ababa, Ethiopia, utilizing thin rib stiffeners and lightweight filling material in between to stabilize the vault. The vault itself was planned to be constructed 60 mm thick by placing two layers of 25 mm thick CEB on top of each other with mortar in between. The rib stiffeners were planned to be 40 mm concrete placed evenly 0.75 m apart. The span was decided to be 3 meters with a span height ratio of 1:10 which gives a vault height of 0.3 m. The supporting beam was a reinforced concrete beam going along the supporting walls. The horizontal forces in the prototype are handled by the concrete beam and steel ties holding the beams together. Calculations of the prototype were performed to ensure that the structure would hold.

The prototype was designed for its self-weight as well as a distributed live load of a school building according to Swedish Standards Institute (2011). A global safety factor of 2.5 was applied to account for uncertainties connected to load and material (Engineering ToolBox, 2010). Asymmetric loading is not considered in calculations of the prototype. The design and spacing of the rib stiffeners in the prototype were done similarly to the stiffeners used in Addis Ababa. The slab structure is similar, and therefore the rib stiffeners in Addis Ababa are deemed useful also in the prototype without further calculations. The horizontal reaction force was calculated with Equation 5.1 (Block et al., 2010). The vertical reaction force was calculated through vertical equilibrium, Equation 5.2. As filling material, pumice was assumed with a density of 250 kg/m^3 and the screed was assumed to be 50 mm concrete with a density of 2400 kg/m^3 . The dimensions of the concrete beam were adjusted to fit inside a compressed u-block, which would be used as lost formwork for the beam. This resulted in the beam-dimension 70x140mm. A limit of four rebars, one in each corner, was set since that is how it is most often done in The Gambia. The needed reinforcement for the set dimensions were calculated to 12 mm bars with 6 mm stirrups every 160 mm. The compressive stress in the vault was calculated to 0.3 MPa. Calculations for the supporting concrete beam is based on Swedish Standards Institute (2008), except from using global safety factors. The calculations can be seen in Appendix E.

$$H = \frac{q * l^2}{8 * h} \quad (5.1)$$

$$V = \frac{q * l}{2} \quad (5.2)$$

where: H = horizontal reaction force [N]
 V = vertical reaction force [N]
 q = distributed load [N/m]
 l = length of the span [m]
 h = height of the vault [m]

5.3 Workshop

The prototype was built in steps taking place at one of Jallow's building sites. The first step was producing the blocks for the vault and thereafter the vault was assembled and the slab finalized.

5.3.1 Production of blocks

The blocks were constructed using earth with 20% clay content. 10% cement was added to shorten the drying time, to enable the workshop to be executed during the field studies. The earth was mixed on the ground with a shovel in small portions to get a fully homogeneous mix, see Figure 5.1a. In the warm weather the moisture content must continuously be checked and altered to be correct. The size of the blocks was decided in discussion together with Jallow, taking the limits of the press into account as well as the mobility of the blocks from the production site to the site of the workshop. The final size of the blocks was 290x140x40mm. A manual press was used where the block size was altered by using varying moulds and distances to the compression mechanism. The earth is poured into the mould and the handle is pulled down compressing the block. When the compression is finished the block is pushed up and carefully moved to where it is left to dry. A picture of the press with a newly pressed CEB can be seen in Figure 5.1b.



(a) Mixing of earth.



(b) CEB machine with newly pressed block.

Figure 5.1: CEB production.

The visual inspection of the blocks is important to ensure that the earth composition and the compression of the block is sufficient. It was challenging to get the blocks equal in thickness along the block, which required some finesse with the settings of the press and several test blocks. When the machine settings were done it was left for the day, and the following day the blocks were produced by Jallow's workers. For optimal flow in the process of producing the blocks, seven people are required for one machine. The workers need good knowledge of how the blocks should look, feel and how they can be moved. The blocks were left to dry for 16 days.

5.3.2 Assembling of slab

The second step was constructing the supporting walls and the formwork for the vault. The span length was changed to 2.44 m and a vault height of 0.255 m, resulting in a ratio of approximately 1:10. This was adjusted due to the size of the plywood used for the formwork of the vaulted shape. The supporting walls were placed directly on the ground and built with bigger earth blocks together with cement mortar, see Figure 5.2a. The supporting beam with the springer for the vault was cast directly on top of the walls using timber boards as formwork as seen in Figure 5.2b. For the springer, one part towards the vault was inclined to create a platform for the blocks to rest on, see Figure 5.2c. The inclination must be verified towards the formwork to ensure that the vault can keep its shape. The original plan of using u-blocks as formwork for casting the beam was disregarded due to the increased work in creating the inclination when using the u-blocks. This resulted in

a larger beam than initially calculated, 150x150mm. Pre-made reinforcement cages were used, with the dimensions 120x75mm. The tension and compression reinforcement were 9 mm bars and the 6 mm stirrups were placed approximately every 300 mm. This was smaller rebars and stirrups placed further apart than initially calculated for, but due to the shorter span, the larger beam dimensions and the prototype not being loaded to the extent of a school building, it was deemed sufficient for the prototype. The formwork for the vault was built out of plywood, using the catenary shape to receive the correct form. The form can partly be seen in Figure 5.2b.

The concrete for the supporting beams was mixed in a wheelbarrow using approximately one wheelbarrow of sand and one 50 kg bag of cement. The dry ingredients were mixed on the ground to a homogeneous mix. Small portions were then lifted into the wheelbarrow and mixed with water before poured into the formwork and vibrated using a masonry trowel and a hammer on the formwork. The steel ties used were reinforcement cages instead of steel ties only. This was decided in discussion with Jallow, who said it was easier to use the pre-assembled reinforcement cages. It was easier to fasten the cage in the other reinforcement, instead of using only one or two bars, even though that would have been sufficient for the capacity. The tie-cages were anchored around the cage in the ring beam to make sure the tie can hold the tension forces, see Figure 5.2d.

5. Prototype of vaulted floor slab



(a) Supporting walls.



(b) Formwork.



(c) Springer with inclined platform.



(d) Reinforcement anchorage.

Figure 5.2: Construction process of the prototype.

When constructing the vault, two layers of blocks with a thin layer of relatively fluid mortar was placed between each block. The blocks were placed in straight rows within the layers, resting on the supporting formwork to achieve the correct shape. The two layers were shifted in relation to each other to prevent continuous

joints through the height of the vault. A mortar thickness of approximately 10 mm was applied between the layers. To achieve good adhesion, the blocks were soaked in water before put in place. The vault was built from two ends and joined in the middle with a keystone. The keystone was cut to fit in the center of the vault to avoid a joint in the center point.

For the filling material, sawdust was mixed together with concrete to create stabilized fill. Sand and cement was mixed with water in a wheelbarrow to a fluid mix and then sawdust was added. The mix was placed on top of the vault, compacted and leveled. The initially planned pumice was hard to get hold of and sawdust was easily accessible from Jallow's wooden workshop. In discussion with Jallow and Rustas, the initial plan was to use sawdust only, but it was later decided to mix it with concrete to increase the weight and the possible compaction level. It was also discussed and decided to disregard the rib stiffeners in the prototype due to lack of time and the fact that stabilised fill is rather heavy and can handle the loads on a prototype well enough without stiffeners. Finally, a concrete screed was cast on top, covering the vault and providing a flat slab. The layers of the vault can be seen in Figure 5.3a. The screed was left to dry over night before removing the formwork and reviewing the result. The prototype was first tested by one person walking over the entire vault. Thereafter it was at the most four people standing on the vault without any visible deformations in the structure, see Figure 5.3b.



(a) Layers of vault.



(b) Prototype load-tested with four people.

Figure 5.3: Final prototype.

5.3.3 Conclusions from workshop execution

From the workshop, conclusions were drawn on how to make the work more efficient and how the prototype was adjusted due to local conditions. One of the conclusions was the importance of working with the modular measurements of the blocks. Through designing the structure with the modular measurements in mind, time and number of blocks can be reduced since less cutting of blocks is needed. Cutting the blocks was time-consuming and the blocks risked cracking. When constructing the vault springer, the vertical support was adapted to the vault shape while the horizontal support did not follow the shape of the brick. The empty space between block and support was therefore filled with mortar. Hence, potential improvement can be made through constructing the support to fit the vault in both vertical and horizontal direction to better transfer the force to the springer. This can be done by creating a 90 degree corner inside the springer to gain full contact area between the brick and the springer. In Figure 5.4, the left sketch indicates what the prototype springer looked like and the sketch to the right the possible improvement. Further, the mortar for the vault was rather coarse with some bigger particles causing problem when applying a thin layer on the blocks. A solution to increase the adhesion would be to remove courser particles before mixing the mortar.

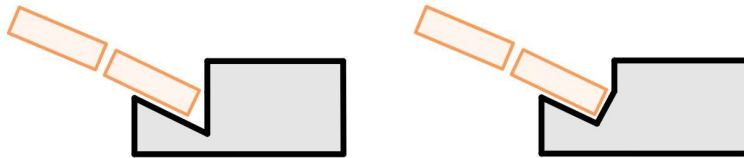


Figure 5.4: Sketch showing possible improvement of the springer shape.

As previously described, the planned rib stiffeners were decided to not be built in the prototype. This due to lack of time and the fact that the prototype will not be loaded with much asymmetric load. The stabilized sawdust was also heavier than the intended pumice, which is beneficial for handling point loads. It was therefore deemed satisfying not using rib stiffeners for this prototype. What was also experienced during the workshop was how easily the blocks crack and break when they are thin. There were three blocks that were visibly cracked when assembling the structure. The cracks were however parallel to the force, hence they will not interfere with the performance of the vault in compression.

5.4 Implementation

In this section, the vaulted floor slab system evaluated in the prototype is adapted and implemented theoretically in a rammed earth school in The Gambia. The floor

slab is adapted to span a standard classroom in the current EB-Elementary design. Further, the supporting structure is designed to satisfy the needs of EB-Elementary.

5.4.1 Investigation of support options

In the beginning of the process of designing a buildable prototype, the decided focus was to find a supporting structure that could work in a modular system and be placed on top of each other to create multiple stories. The biggest challenge concerning the supporting structure is to handle the horizontal forces, which was the main focus in the initial step. Several alternative solutions were found and can be seen in Figure 5.5. The span was set to 7.5 m, based on the latest design of a classroom in EB-Elementary. Early in the process Jallow expressed a desire to not show any tension ties underneath the vault as seen in Figure 5.5a. Therefore some other alternatives were invented and evaluated.

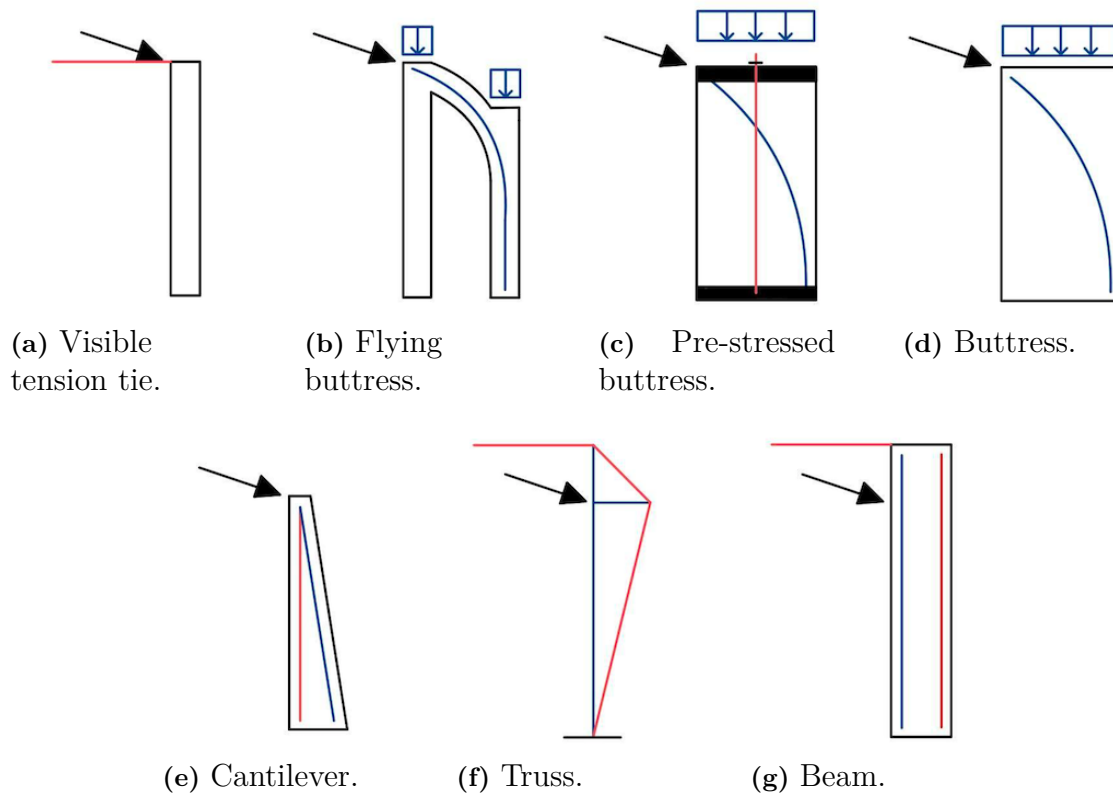


Figure 5.5: Supporting options for the vaulted slab.

Flying buttresses, Figure 5.5b, were considered too spacious for a modular structure and the pre-stressed buttress, Figure 5.5c, was considered too complex to produce in the local context. The remaining alternatives were then evaluated through rough calculations, approximating dimensions and spacing of the different supporting options.

In collaboration with Simon Rustas, support dimensions that could be allowed for the system was decided to 0.5 m width and a thickness of 0.25 m. From brief cal-

culations and evaluation, it was realized that the buttress solution, Figure 5.5d, required much wider support or a steeper loading angle, meaning a higher vault. The buttress solution was therefore not further considered.

The cantilever, seen in Figure 5.5e, only allowed small spans when the support was limited to 0.5 m width. Therefore this solution was also deemed unsuitable. Both the truss, Figure 5.5f, and the beam support, Figure 5.5g, would allow for relatively long spans without exceeding the decided dimensions. The beam, which has a hidden steel tie in the slab above the vault, was considered a better alternative in this context since the beam can be cast with CEB or rammed earth as lost formwork. Additionally, the concrete pillar provide stabilization to the wall, which the truss would not necessarily do.

The most feasible solution for the modular system without visible steel ties was shown to be the beam solution with steel ties above the vault, see Figure 5.5g. The shallower the vault, the more efficient this solution becomes, which is considered positive when constructing a floor slab.

However, if multiple storeys are sought for in the design of the EB-Elementary, it is deemed a better solution to have visible steel ties in the roof, as in Figure 5.5a, to simplify the load paths and avoid unnecessary use of material in the supporting beams. Some ties can be hidden in the dividing walls.

5.4.2 Conclusions regarding shallow vaulted slab in school building

It is important that the slab can hold for unequal loads, for example if the whole class moves together into one corner of the classroom. The concentrated load must be handled and distributed by the filling material and the rib stiffeners that is advised to be used in the slab. Regarding filling material, it is not suitable to use stabilized sawdust in a school building since there is a risk for termites as well as the sawdust rotting inside the slab. Pumice could be a possible solution for filling material, similar to the vault in Addis Ababa. Although, pumice can be difficult to get hold of in The Gambia and therefore expanded polystyrene (EPS) could be a suitable alternative, if used together with rib stiffeners. According to Jallow, EPS can be found in the country and will not experience any trouble with termites (personal interaction, 7 of May, 2023). Though, it is important that rib stiffeners are added to the structure since EPS is lightweight. The rib stiffeners can be made of e.g. concrete or earth blocks.

5.4.3 Conclusions regarding shallow vaulted slab in rammed earth building

When working with a shallow vaulted slab in a rammed earth building, some details and aspects must be considered when designing and building. One of the most important parts of the vaulted slab is the springer, where the vault lands on the

vertical supports. When implementing a CEB vault in a rammed earth building with concrete ring beam, the ring beam can be used as springer by tilting a part of the beam to meet the adjoining blocks. However, this implies that the rammed wall on top of the ring beam must be thinner than the wall below, since the inclined part reduces the top width of the beam, see sketch to the left in Figure 5.6. Another option is to make an opening in the ring beam and let the upper wall be as thick as the lower, see sketch to the right in Figure 5.6. It is however common in two-storey buildings of rammed earth to have the upper wall thinner, since it must not handle as much compression as the lower wall. Therefore, it is preferred to make the upper wall thinner to reduce the material needed. What also must be verified regarding the upper wall is its capacity of handling the horizontal forces coming from i.a. filling material, screed and people standing close to the wall.

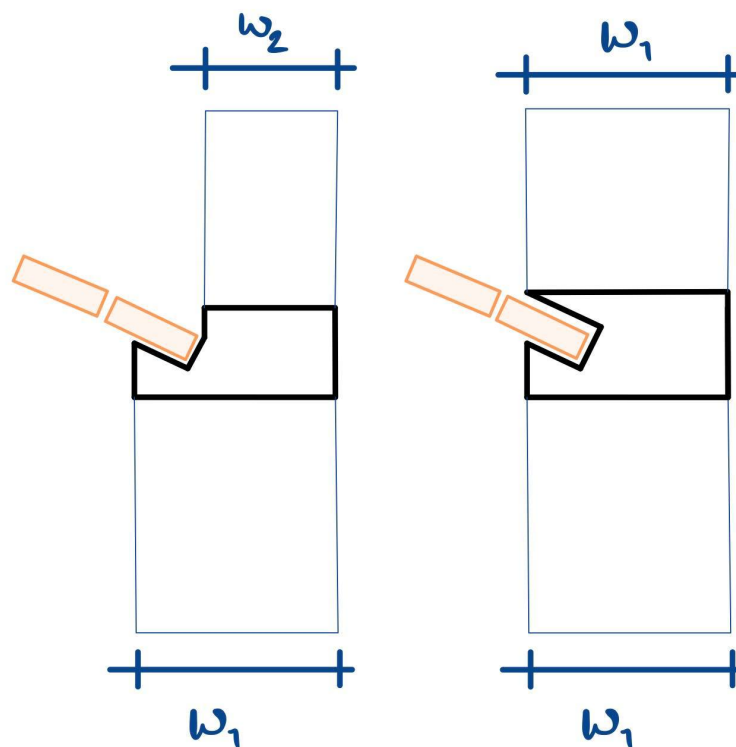


Figure 5.6: Sketch showing how the wall thickness can be adapted to the springer shape.

One benefit from using rammed earth together with the CEB slab is that the ramming formwork possibly can be used as casting formwork for the ring beam, with added parts to create the inclination. Wood and wooden boards are rather expensive and not as common in The Gambia as in Sweden. Therefore, reusing as much formwork as possible is beneficial for a project.

It is advisable to have a movable formwork when building larger vaults. When constructing the prototype, formwork covering the entire span was used. However, when a deeper vault is constructed, a non-movable formwork covering the entire

vault depth would be in the way when building as well as require a large amount of wooden boards, which is expensive. A movable formwork must be constructed so that it can easily be attached and moved along the vault depth. Though, the formwork must always be controlled to sit perfectly in relation to the springer to ensure that the shape of the vault becomes correct.

From the building process of the prototype, it was realized that a suitable workflow of constructing the slab in connection to a rammed earth wall would be to ram the lower walls and thereafter cast the ring beam on top, including the reinforcement and the tension ties holding the vault together. Thereafter parts of the next wall on top should be rammed, slightly higher than the total slab height. This is so that the slab can be finished with filling material and screed while still having the possibility of working from the outside as well as from below when constructing the vault and slab. The part of the wall above the finalized slab is for attaching the ramming formwork for ramming the remaining part of the upper wall.

5.4.4 Design proposal of slab

Calculations of shallow vaulted slab for a school building was performed to achieve a design proposal of a slab. The span is assumed 7.5 m and the ratio 1:10 results in a vault height of 0.75 m and a total slab height of 0.8 m. Firstly, the thickness of the walls are assumed 350 mm and 380 mm, same as in Section 4.5. They are checked for loads from the roof, assuming a roof weight of 40 kg/m², upper wall and the slab. Both walls are well below the decided capacity of 2 MPa.

Secondly, the thickness of the wall is put as limit to the width of the ring beam and the needed reinforcement is calculated for the beam to hold the horizontal forces from the slab. Thirdly the spacing between steel ties is calculated. Live load for a school according to Swedish Standards Institute (2011) is applied with a global safety factor of 2.5. Detailed calculations and results can be seen in Appendix F.

The ring beam between the walls has the same width as the lower wall, 380 mm, to utilize the full wall thickness and to simplify the formwork for casting. The steel ties complementing the ring beam in holding the vault together has a diameter of 10 mm and are needed every third meter in the building. It is important to ensure sufficient load transfer between the ring beam and the steel tie.

The same earth blocks as for the prototype is used for the vault, 290x140x40 mm. One centimeter of mortar is assumed between the blocks and EPS is used as filling material. On top of the EPS there is five centimeter of concrete screed. Amongst the EPS there are rib stiffeners every 0.75 m made out of concrete. It is decided to not use blocks for rib stiffeners due to the thin blocks being rather difficult to cut into the correct shape following the vault, without cracking the blocks.

6

Discussion

This thesis has to a great extent been defined by opportunities and meetings throughout the process. The initial plan has been developed and redefined several times due to possibilities that have arisen, both during the pre-study and the field studies. However, the core topics of rammed earth with the Gambian context and the school context has remained throughout the project while the method and the content have changed. Firstly, a greater focus on rammed earth in The Gambia was planned before the field studies started. A meeting with an entrepreneur working with rammed earth in a modern context was arranged, but he later announced that the meeting and planned day to work alongside him was canceled due to personal reasons. It was also realized that there were not many rammed earth houses visible in the urban area of The Gambia, while CEB buildings were more common. Instead, two CEB builders were visited, which led the field studies more towards earth building in general in The Gambia, rather than rammed earth only. This also enabled working with the floor slab prototype in CEB, instead of a rammed earth workshop that was the initial idea.

6.1 Design process

In this thesis, the building material is the starting point. From there, the context has been considered, leading to design suggestions. This approach is different from the more common process where the design is based on the context and a suitable building material is chosen to achieve the desired design. In a process where the building material sets the standard, the material properties become governing in the design. For example, the compressive strength requires thick walls and surrounding structures, like the roof, to be adapted to suit the needs of the chosen material. In the more common design process, the design becomes governing and the choice of building material becomes subordinated to the design. For example, in a design with big openings, only a few building materials can handle the span, which results in one of those materials being chosen rather than the size of the opening being changed. This workflow, starting with the material, can be easily integrated with a holistic workflow where the various professions in the design of a building can collaborate early in the process to avoid clashes. This has been experienced in the process together with Detail Group, who are continuously working with the architectural design of EB-Elementary in collaboration with EarthLAB Studio.

When the thesis was initiated, the school design consisted of two-storey buildings with only some walls built with rammed earth. Halfway through the thesis, the design changed to one-storey buildings with all walls built in rammed earth. This change resulted in the already planned workshop for the slab prototype to be evaluated again. It was decided that the prototype was still to be built and could give value to the project if the design was to be changed again to a two-storey building. Further, working with the prototype gave valuable insights regarding a Gambian building process.

The final choices of details have a holistic approach where input from people and builders we have met form the knowledge basis. That does not necessarily mean that it is the full truth applicable everywhere. For example, our perception of the availability of building materials is based on what the builders we have met have told us, as well as what we have seen in the urban area. That does not mean that other builders will not say something else or that the availability is the same in other parts of the country. Most likely it is not. The final choices of detail solutions are sometimes based on each other, therefore, if one detail is changed the others should be re-evaluated and possibly changed to suit the new conditions better. The holistic approach may not give the optimal solution for every specific detail, but the design and buildability of the whole structure were deemed more important.

6.2 Compression tests

The idea with the test equipment was to create a test method to easily evaluate the compressive strength on site. The test method can be used to find suitable earth before paying for lab tests as well as to continuously control the compressive strength. The test method can fulfill its purpose and give an estimation of the compression strength if validated with lab tests, which would be the first step in development work. However, lab tests are always recommended before a full-scale project is initiated.

The compression tests carried out showed the same compression strength both with and without cement stabilizer which does not correspond with literature. This probably depends on the mixing, ramming, or the test method itself. The compression strength depends on many factors and the manual testing process makes it hard to evaluate only one of the parameters.

6.3 Uncertainties

There are many uncertainties when building in The Gambia, both regarding materials and construction methods used. Many decisions are made on the construction site based on the material and tools available, which can make it hard to predict the outcome and make accurate calculations on the structure beforehand. Supervision

of the work, either from the designer or a well informed constructor, is important if special details or procedures are required.

During the field studies, we could not get hold of any current building regulations or tables of material properties for The Gambia. There might be such regulations existing, but they were not accessible to us, which is why the calculations performed in this thesis use global safety factors to take the uncertainties of loads and materials into account. It was decided not to use safety factors from Eurocode, since Eurocode is not followed in The Gambia and is difficult to use when the exact properties of the materials used on site are unknown. For example, concrete is usually mixed using wheelbarrows as measuring units, and no further specifications are made, e.g. water-cement ratio or the size distribution of the aggregates. The concrete is mixed with the sand available and water is added until it is visually deemed suitable.

Another uncertainty can be the quality of the building products. For example, civil engineer Augustine Manneh says that the quality and strength of reinforcement bars have been decreasing lately (personal interaction, 6 of April, 2023). This is considered by sometimes using a larger bar diameter to reduce the risk of lower quality affecting the structure. This can be considered a safety factor applied to the structure outside of calculations.

A global safety factor of 2.5 was chosen based on general safety factors for a structure, found, amongst others, at Engineering ToolBox (2010). The factor takes into account the reliability of the material as well as how severe the environmental and loading conditions are. The safety factor 2.5 was chosen since it is on the limit between the cases of regular and less tested materials. The safety factor is applied by amplifying the loads in the calculations.

The calculations performed in this thesis are simplified to get an estimation of the performance of an element. This is partly because the design of the school is still in the design phase and will change in the future. Moreover, making detailed calculations for every detail was considered too time-consuming. That is also why the wind load is not considered. Many assumptions had to be made regarding material properties and loads since no norms or well-established documentation of materials was available to us. Therefore, more detailed calculations and well-informed assumptions are needed before using any of the proposed designs in this thesis.

Overall, throughout this thesis work there has been a lot of assumptions and uncertainties for us to deal with, both regarding calculations and the results, which are often based on conversations and our perception of a situation. This has caused long discussions on how to take the uncertainties into account, what means to use to reduce them and how to cover all potential spectres in a complex matter.

We experienced several uncertainties connected to a structure, especially in The Gambia, that must be considered. We struggled with trusting our own assumptions and calculations, especially when we did not have any regulations or examples to

follow, nor any values for the material properties to use. We realized that this is what it can look like in "real life" and that we must learn to cope with the uncertainties and trust our own ability to make assumptions.

Although, it is important to realize that what we consider assumptions and uncertainties, is not necessarily an assumption for the Gambians. Since we are used to working with detailed standards in Sweden, we considered processes not following the same steps as uncertainties. The Gambian process looks different but seems trusted since they have used it through history. If we as engineers from Sweden would have provided a design based on calculations, asking them to change how they usually do things, they would probably see it as an uncertainty and not trust it to the same extent. These varying points of view must be considered and integrated in a collaboration between the different perspectives, and in this case, we as visitors tried to adapt and trust in their experience.

Our perception is that the constructors in The Gambia generally are more involved in design process and trusted to make decisions during the process. They also seem to be more accustomed to adapting to changes. This is something that might be beneficial also in the Swedish construction industry. The decision making could be closer to the construction site and include and value the experience of the constructor to a higher extent.

6.4 Prototype collaboration

The workshop included three professions, one architect, two structural engineers, and one CEB constructor, who all worked together in both the design and the production. There was an initial plan for how the slab could be built, coming mainly from the architect and the structural engineers, with inputs from the constructor. When the construction started, changes were made throughout the construction for various reasons, e.g. lack of building material, or second thoughts from the constructor of how it could be built in an efficient way.

The constant changes required discussions within the group to verify that everyone could agree to the changes. Our initial plan was to work with the mindset of all of us being the clients with equal interests and equal say. This worked partly, but the constructor had the final say in several discussions since he knows the most about constructing with CEB and what materials are available in the area. Still, there were many discussions where everyone brought up their opinion and a common decision was made.

What was learned from this process is the importance of everyone being involved to pursue what is important to them in the structure or building. As structural engineers, we sometimes found it to be a frustrating process where rethinking and recalculations were needed quickly to ensure that the new structure would hold. At the same time, it was an interesting process where we learned from the other

professions. It also increased our ability to collaborate and know when to argue for our own perspective and when someone else's perspective is more important.

The final design of the prototype did not turn out as the two of us initially planned, but we are satisfied with the result and that it could hold the four of us standing on top of it. We learned a lot from the process, both regarding construction with CEB as well as collaboration between professions and what an ongoing design process can look like.

6.5 Perception of earth building

During the field studies, it was recognized that the perception of earth building in The Gambia was overall negative. Many locals associate earth buildings with the past and consider it an outdated building material for poor people on the countryside. Most importantly, earth buildings are not considered durable enough during the rainy season. For people in The Gambia, especially the poorer people, a destroyed house is devastating for the family. It can take years to finance the construction of a new home, therefore having a house that feels durable and safe is sought for. People talk about the comfort of staying in an earth house and how cool the temperature is when it is warm outdoors. Still, the concrete houses are chosen in the end because they are deemed to withstand the water better and are therefore more trusted.

In the beginning of the thesis, no stabilizers were considered and cement-stabilized rammed earth was part of the demarcations, but during the field study, interesting insights were made. After discussions with the local population and constructors, it became clear that many clients want to add cement stabilizers to feel safe living in an earth house. If adding a small amount of cement to the mix makes the client, or the constructor, feel safer it might be a necessary addition similar to adding safety factors as done when dimensioning buildings in Sweden.

The initial idea of the workshop, planned before the field studies, was to build something with rammed earth at the site for EB-Elementary. This to show the inhabitants in the neighborhood what the school would be made of and that earth can be used as building material in a modern building. It was also planned to have the children and their parents be part of the workshop and help ramming as a way of showing how simple the construction method is. The rammed earth workshop was not carried out and one of the main reasons for that is the rather negative perception of earth buildings. A physical representation of rammed earth can be a good way of showing that earth building can be part of modern construction and that it can be trusted. However, it is utterly important that the representation shows the possibilities and not the disadvantages with rammed earth. If a poor representation is placed on the site, e.g. where the erosion is large or where it starts to fail after a few years, it is a considerable risk that the perception of earth building gets worse and that no one will trust the school when it is later built. Therefore, no rammed earth workshop was performed since the risk of creating a bad representation over

time was deemed greater than the possibility of creating a positive representation within the time frame. It was realized that it would have taken too much time and resources to build a foundation and roof good enough to protect the rammed earth from rain, to be reasonable to execute within the eight weeks of field studies. Having a workshop where the locals can be part of ramming and creating something that stands and look durable would be a great step for spreading trust of earth building, though it must be planned and performed carefully to succeed.

As said in the previous section, physical examples of earth buildings are most likely the best way to spread trust and knowledge about earth building. If successful earth constructions can be seen and touched, it is easier to believe in. Rammed earth has great potential for the future, however, if the goal is to spread earth construction in general in The Gambia, using CEB might be a better first step towards the goal in this context and time. The construction method of assembling blocks is similar to the concrete blocks that are commonly used today and the method is therefore easily accessible for construction workers. Further, there are no special tools required for assembling the earth blocks compared to concrete blocks. What is needed to go from concrete blocks to CEB is a press that produces the blocks. Compared to a rammed earth building where formwork and rammers are required, the CEB construction requires the same tools as the ones already widely used. Furthermore, the shape of a block seems to symbolize development, industrialization, and modernity to the people in The Gambia. Rather than pouring earth from the ground and pounding it by hand, the blocks are processed in a machine, which seems to feel more trustworthy. Still, if a rammed earth building is constructed in a good way and the skill of ramming is taught to people in The Gambia, the building would show a great example of how earth can be used and increase the chance of rammed earth as building technique being spread.

6.6 Outlook

If further research would be performed within the topic of this thesis, interesting outlooks are:

- Develop the test method and verify it with lab results to gain a trustworthy test method that can be used on site.
- Evaluate different earth types in The Gambia to see if there are earth types more suitable for rammed earth.
- Further investigation of the slab solution and how the building process of the slab can be efficient in a real structure. What filling material to use and how the rib stiffeners are designed efficiently?
- Connections between wall and roof together with an investigation of whether a heavy or light-weight roof structure is most efficient.
- Investigation of the erosion due to school activities to see how much calculated erosion would be needed, e.g. by letting kids play football against a rammed earth wall and see how much it is affected.

- A cost comparison of the different solutions to see if the final choices would change due to that aspect.
- A carbon-dioxide equivalent comparison of the different solutions to see if the final choices would change due to that aspect.
- How rammed earth technique can be taught efficiently through training programs contributing to a spread of knowledge within the field of earth building.

7

Conclusion

It was concluded during the field studies that design must be carefully adapted to the local conditions. There are rarely any solutions that are applicable everywhere in the world and the design process should therefore be adapted and rooted in the local context.

There are many aspects to consider when building a school in rammed earth in The Gambia. The chosen material together with local conditions sets high demands on the structure and hence the design. Local weather conditions make protection against water the outermost important design criterion. Further, protection against water is a key point to prove and convince the common man in The Gambia that building with rammed earth is an option in a modern context.

According to the preliminary test results, the properties of the selected local earth mixes evaluated in The Gambia are not suitable for rammed earth constructions. Further earth samples should be tested in a lab to establish its suitability. If the earth is not found suitable, another earth should be tested, or stabilizers should be added to ensure sufficient structural properties. The developed method for compression tests should not be used as the only evaluation method.

When building with rammed earth in The Gambia, supervision by the designer or a well informed constructor is highly recommended, especially for the critical details.

The prototype of a shallow vaulted slab was successful and could carry four persons. The conceptual design of the slab is deemed possible also on a larger scale and in a rammed earth building, with required adaptations and further calculations.

Overall, it is concluded that the school most likely can be built with rammed earth if suitable earth is found in The Gambia. Certain details must be carefully designed and executed to adjust to the context of a school in The Gambia.

Bibliography

- Block, P., DeJong, M., Davis, L., & Ochsendorf, J. (2010). Tile vaulted systems for low-cost construction in Africa. *ATDF JOURNAL*, 7(1/2), 4–13.
- EarthLAB Studio. (n.d.). *IN-FORM* (tech. rep.).
- Easton, D. (2007). *The Rammed Earth House* (J. Barstow & C. Labrie, Eds.; Vol. Rev. Ed). Chelsea Green Publishing Company.
- Engineering ToolBox. (2010). Factors of Safety. https://www.engineeringtoolbox.com/factors-safety-fos-d_1624.html
- Erden. (2022). *Design Guide for Rammed Earth* (tech. rep.). <https://www.erden.at/Design-Guide>
- Erika Alatalo. (2019). Build with Gambia Earth Architecture Workshop: Experimenting with local materials in rural Gambia - Field Study of the World. <https://www.fieldstudyoftheworld.com/build-with-gambia-earth-architecture-workshop-experimenting-with-local-materials-in-rural-gambia/>
- Fabbri, A., Morel, J.-C., Aubert, J.-E., Bui, Q.-B., Gallipoli, D., & Reddy, B. V. (Eds.). (2022). *Testing and Characterisation of Earth-based Building Materials and Elements* (Vol. 35). Springer International Publishing. <https://doi.org/10.1007/978-3-030-83297-1>
- Gapminder. (n.d.-a). Gapminder Tools - Primary school completion. [https://www.gapminder.org/tools/#\\$model\\$markers\\$bubble\\$encoding\\$y\\$data\\$concept=primary_completion_rate_total_percent_of_relevant_age_group&space@=country&=time;;&scale\\$domain:null&zoomed:null&type:null;;&x\\$data\\$concept=time&space@=time;;&scale\\$domain:null&zoomed:null&type:null;;&frame\\$value=2021;&trail\\$data\\$filter\\$markers\\$gmb=1971;;;;;;&chart-type=bubbles&url=v1](https://www.gapminder.org/tools/#$model$markers$bubble$encodingydata$concept=primary_completion_rate_total_percent_of_relevant_age_group&space@=country&=time;;&scale$domain:null&zoomed:null&type:null;;&x$data$concept=time&space@=time;;&scale$domain:null&zoomed:null&type:null;;&frame$value=2021;&trail$data$filter$markers$gmb=1971;;;;;;&chart-type=bubbles&url=v1)
- Gapminder. (n.d.-b). Gapminder Tools: Income. [https://www.gapminder.org/tools/#\\$ui\\$chart\\$opacitySelectDim:0.23;;&model\\$markers\\$bubble\\$encoding\\$y\\$data\\$concept=income_per_person_gdpper capita_ppp_inflation_adjusted&space@=country&=time;;&scale\\$domain:null&zoomed:null&type:null;;&x\\$data\\$concept=time&space@=time;;&scale\\$domain:null&zoomed:null&type:null;;&frame\\$speed:393;&trail\\$data\\$filter\\$markers\\$gmb=2022&swe=2022;;;;;;&chart-type=bubbles&url=v1](https://www.gapminder.org/tools/#uichart$opacitySelectDim:0.23;;&model$markers$bubble$encoding$y$data$concept=income_per_person_gdpper capita_ppp_inflation_adjusted&space@=country&=time;;&scale$domain:null&zoomed:null&type:null;;&x$data$concept=time&space@=time;;&scale$domain:null&zoomed:null&type:null;;&frame$speed:393;&trail$data$filter$markers$gmb=2022&swe=2022;;;;;;&chart-type=bubbles&url=v1)
- Globalis, S. F. f. (n.d.). Gambia. <https://www.globalis.se/Laender/gambia>
- Keable, J., & Keable, R. (1996). *Rammed Earth Structures*. <https://doi.org/10.3362/9781780440668>
- Lee, E. (2020). *Comparative approaches to rammed earth building standards in different nations* (tech. rep.). Department of Architecture and Architectural Engineering, Yonsei University. Seoul.

- Matsdotter, V. (2020). *Down to Earth: circular material flows & resource salvation* (tech. rep.).
- Minke, G. (2006). *Building With Earth - Design and Technology of Sustainable Architecture* (Vol. N/A).
- Nderi, I. (2021). Children of Gambia - Humanium. <https://www.humanium.org/en/gambia/>
- Olsson, M. (2022). *Unlocking Earth* (Doctoral dissertation). Chalmers University of Technology. Gothenburg.
- Otcovská, T. P., Mužíková, B., & Padevět, P. (2019). Mechanical properties of rammed earth with respect to clay mixture composition. *Acta Polytechnica*, 59(4), 372–383. <https://doi.org/10.14311/AP.2019.59.0372>
- SADCSTAN. (2014). SADC HARMONIZED STANDARD FOR RAMMED EARTH STRUCTURES-CODE OF PRACTICE THC 03.
- Schildkamp, M. (2009). *Suitability of Local Soil for Cost Saving Construction Techniques (with test results of soil samples from Kaski District in Nepal)* (tech. rep.).
- Swedish Standards Institute. (2011). SS-EN 1991-1-1. www.eurokoder.se,
- Swedish Standards Institute. (2008). SS-EN 1992-1-1:2005. www.eurokoder.se,
- The Gambia Standards Bureau. (2018). *National Standardization strategy - 2018 - 2020* (tech. rep.). https://tgsb.gm/sites/default/files/2020-11/NSS-2018_2020_2.pdf
- The Republic of The Gambia. (1988). *A CULTURAL POLICY FOR THE GAMBIA*, Ministry of Education, Youth, Sports and Culture. https://en.unesco.org/creativity/sites/creativity/files/qpr/a_cultural_policy_for_the_gambia_1988.pdf
- The Republic of The Gambia. (2002). *CONSTITUTION OF THE REPUBLIC OF THE GAMBIA, 1997* (tech. rep.). <http://hrlibrary.umn.edu/research/gambia-constitution.pdf>
- The Republic of The Gambia. (1996). *National report and plan of action on human settlements 1996-2000* (tech. rep.). Banjul. <https://habitat3.org/wp-content/uploads/Habitat-II-NR-1996-GAMBIA.pdf>
- The World Bank. (2022). Literacy rate, youth total (% of people ages 15-24) - Gambia, The | Data. <https://data.worldbank.org/indicator/SE.ADT.1524.LT.ZS?locations=GM>
- The World Bank Group. (2021a). Sweden - Climatology | Climate Change Knowledge Portal. <https://climateknowledgeportal.worldbank.org/country/sweden/climate-data-historical>
- The World Bank Group. (2021b). The Gambia - Climatology | Climate Change Knowledge Portal. <https://climateknowledgeportal.worldbank.org/country/gambia/climate-data-historical>
- The World Bank Group. (2021c). The Gambia - Vulnerability | Climate Change Knowledge Portal. <https://climateknowledgeportal.worldbank.org/country/gambia/vulnerability>
- UN General Assembly. (1989). *CONVENTION ON THE RIGHTS OF THE CHILD* (tech. rep.).

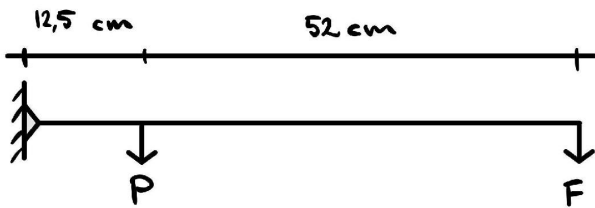
- UNDP & The Republic of The Gambia. (2020). *The Gambia National Development Plan (2018-2021)* (tech. rep.). <https://gambia.un.org/sites/default/files/2020-10/1.-The-Gambia-National-Development-Plan-2018-2021-Full-Version.pdf>
- Walker, P., Keable, R., Martin, J., & Maniatidis, V. (2005). *Rammed earth : design and construction guidelines*, 146.

A

Test 1 in Sweden

Script to calculate applied stress on specimen

Model of compression equipment. Force is applied in F and P act on the specimen.



```
clear all
clc

% Input
m=175;           % Applied force [kg]- Variable
g=9.82;         % [m/s^2]
F=m*g;          % [N]
P=F*65.5/12.5   % [N]
```

```
P = 9.0049e+03
```

```
% Circular specimen
d=0.037;        % [m]
A_cir=(d/2)^2*pi; % [m^2]
sigma_cir=P/A_cir*10^-6; % [MPa]
```

```
% Rectangular specimen
b=0.06; % [m]
h=0.06; % [m]
A_rec=b*h;
sigma_rec=P/A_rec*10^-6 % [MPa]
```

```
sigma_rec = 2.5014
```

```
% Calculation to take extra material into account
% according to EC for concrete (Eq. 6.63)
A_c1=0.14*0.11;
sigma_adj=P/(A_rec*sqrt(A_c1/A_rec))*10^-6 % [MPa]
```

```
sigma_adj = 1.2094
```

B

Test 2 in Sweden

10% mix

Area cylinder [m²]: 0,001075

Original height [mm]: 79,5

Mix with 10% - Cylinder 1					
Load		Result			
m [kg]	F [N]	P [N]	δ [mm]	ε [-]	σ [MPa]
0	0	0,0	79,5	0	0,000
10	98	514,6	77,5	0,025157	0,479
20	196	1029,1	77	0,031447	0,957
25	246	1286,4	77	0,031447	1,196
30	295	1543,7	77	0,031447	1,436
33	324	1698,1	77	0,031447	1,579
35	344	1801,0	77	0,031447	1,675
37	363	1903,9	77	0,031447	1,771
31	304	1595,2	77	0,031447	1,484

Hear when start cracking. Start cracking in the bottom (latest rammed).
Brittle diagonal failure.

Original height [mm]: 81

Mix with 10% - Cylinder 2					
Load		Result			
m [kg]	F [N]	P [N]	δ [mm]	ε [-]	σ [MPa]
0	0	0,0	81	0	0,000
10	98	514,6	79	0,024691	0,479
15	147	771,9	79	0,024691	0,718
20	196	1029,1	79	0,024691	0,957
25	246	1286,4	78,5	0,030864	1,196
30	295	1543,7	78	0,037037	1,436
35	344	1801,0	78	0,037037	1,675
36	354	1852,4		1	1,723
	0	0,0		1	0,000

Crushing on top (latest rammed).

b [m]: 0,045

h [m]: 0,045

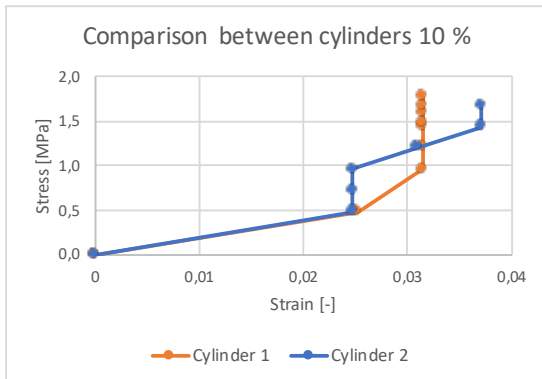
Area [m²]: 0,002025

Original height [mm]: 103

Mix with 10% - Block					
Load		Result			
m	F	P	δ	ε [-]	σ
20	196	1029,1	103	0	0,508
40	393	2058,3	102,2	0,007767	1,016
60	589	3087,4	102	0,009709	1,525
80	786	4116,5	101,1	0,018447	2,033
100	982	5145,7	101,1	0,018447	2,541
110	1080	5660,2	100,8	0,021359	2,795
115	1129	5917,5	99	0,038835	2,922
109	1070	5608,8	99	0,038835	2,770

Crack load:			
m	F	P	σ
100	982	5145,7	2,541

At 109 kg applied load there is a 7 mm wide crack. A 2 mm deep compression mark was seen after unloading.



15% mix

Area cylinder [m²]: 0,001075

Original height [mm]: 77

Mix with 15% - Cylinder 1					
Load		Result			
m [kg]	F [N]	P [N]	δ [mm]	ε [-]	σ [MPa]
0	0	0,0	77	0	0,000
10	98	514,6	76	0,012987	0,479
20	196	1029,1	76	0,012987	0,957
30	295	1543,7	76	0,012987	1,436
37	363	1903,9	74	0,038961	1,771

Original height [mm]: 77

Mix with 15% - Cylinder 2					
Load		Result			
m [kg]	F [N]	P [N]	δ [mm]	ε [-]	σ [MPa]
0	0	0,0	77	0	0,000
10	98	514,6	76	0,012987	0,479
15	147	771,9	74	0,038961	0,718
20	196	1029,1	73,5	0,045455	0,957
22	216	1132,0		1	1,053

Crack at 15 kg load. Trickier to ram hard in the top of the form. The layer rammed latest failed first. This was examined through testing one of the cylinders upside-down.

b [m]: 0,045

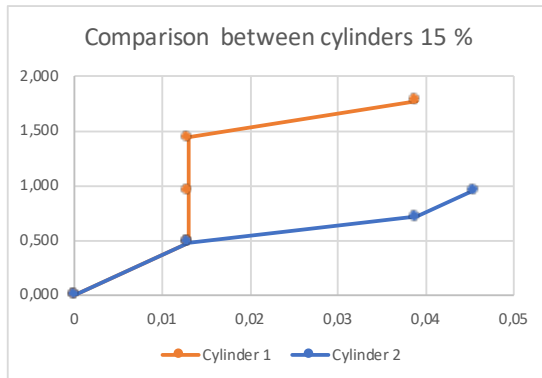
h [m]: 0,045

Area [m²]: 0,002025

Original height [mm]: 108

Mix with 15% - Block						Crack load:			
Load		Result				m	F	P	σ
m	F	P	δ	ε [-]	σ				
20	196	1029,1	106,5	0,013889	0,508	140	1375	7204,0	3,558
40	393	2058,3	106	0,018519	1,016				
60	589	3087,4	106	0,018519	1,525				
80	786	4116,5	106	0,018519	2,033				
100	982	5145,7	105,9	0,019444	2,541				
120	1178	6174,8	105,8	0,02037	3,049				
130	1277	6689,4	105,5	0,023148	3,303				
140	1375	7204,0	105	0,027778	3,558				
150	1473	7718,5	105	0,027778	3,812				
160	1571	8233,1	104	0,037037	4,066				
170	1669	8747,7	103,2	0,044444	4,320				
156	1532	8027,3	102,5	0,050926	3,964				

2 mm depth of compression mark.



20% mix

Area cylinder [m²]: 0,001075

Original height [mm]: 81

Mix with 20% - Cylinder 1					
Load		Result			
m [kg]	F [N]	P [N]	δ [mm]	ε [-]	σ [MPa]
0	0	0,0	81	0	0,000
10	98	514,6	79	0,024691	0,479
15	147	771,9	79	0,024691	0,718
20	196	1029,1	77	0,049383	0,957
25	246	1286,4	76,5	0,055556	1,196
26	255	1337,9		1	1,244
	0	0,0		1	0,000

Uneven distribution of particles can be reason to more crushing.
Crushed in the layer that was rammed first.

Original height [mm]: 83

Mix with 20% - Cylinder 2					
Load		Result			
m [kg]	F [N]	P [N]	δ [mm]	ε [-]	σ [MPa]
0	0	0,0	83	0	0,000
10	98	514,6	82	0,012048	0,479
15	147	771,9	81	0,024096	0,718
20	196	1029,1	81	0,024096	0,957
25	246	1286,4	81	0,024096	1,196
30	295	1543,7	81	0,024096	1,436
34	334	1749,5		1	1,627

Crushing through the whole specimen but more towards the layer that was rammed first.

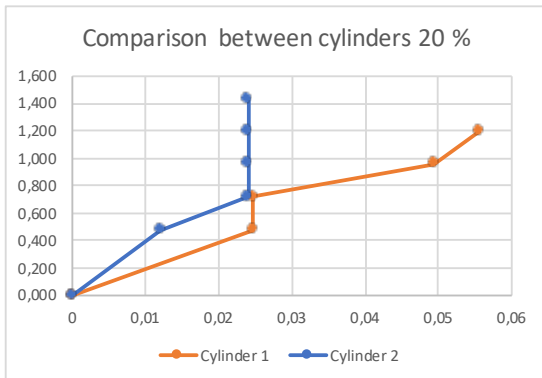
b [m]: 0,045

h [m]: 0,045

Area [m²]: 0,002025

Original height [mm]: 107

Mix with 20% - Block						Crack load:			
Load		Result				m	F	P	σ
m	F	P	δ	ε [-]	σ				
10	98	514,6	106,5	0,004673	0,254	120	1178	6174,8	3,049
20	196	1029,1	106	0,009346	0,508				
30	295	1543,7	105,5	0,014019	0,762				
40	393	2058,3	105,5	0,014019	1,016				
50	491	2572,8	105,1	0,017757	1,271				
60	589	3087,4	105,1	0,017757	1,525				
70	687	3602,0	105,1	0,017757	1,779				
80	786	4116,5	105	0,018692	2,033				
90	884	4631,1	105	0,018692	2,287				
100	982	5145,7	104,8	0,020561	2,541				
110	1080	5660,2	104,8	0,020561	2,795				
120	1178	6174,8	104,5	0,023364	3,049				
130	1277	6689,4	104	0,028037	3,303				
140	1375	7204,0	104	0,028037	3,558				
150	1473	7718,5	103	0,037383	3,812				
144	1414	7409,8	103	0,037383	3,659				



Unknown% mix

Area cylinder [m²]: 0,001075 Lite fler lager.

Original height [mm]: 80

Mix unknown - Cylinder 1					
Load		Result			
m [kg]	F [N]	P [N]	δ [mm]	ε [-]	σ [MPa]
0	0	0,0	80	0	0,000
10	98	514,6	79	0,0125	0,479
15	147	771,9	78,5	0,01875	0,718
20	196	1029,1	78,5	0,01875	0,957
25	246	1286,4	77,5	0,03125	1,196
26	255	1337,9		1	1,244
	0	0,0		1	0,000
	0	0,0		1	0,000
	0	0,0		1	0,000

More layers

Original height [mm]: 79

Mix unknown - Cylinder 2					
Load		Result			
m [kg]	F [N]	P [N]	δ [mm]	ε [-]	σ [MPa]
0	0	0,0	79	0	0,000
10	98	514,6	78	0,012658	0,479
15	147	771,9	78	0,012658	0,718
20	196	1029,1	78	0,012658	0,957
25	246	1286,4	77,5	0,018987	1,196
30	295	1543,7	77	0,025316	1,436
35	344	1801,0	77	0,025316	1,675
40	393	2058,3	76,5	0,031646	1,914
40	393	2058,3		1	1,914

Broke in a layer before starting the test. Diagonal crack failure. Break into layers with precise cut.

b [m]: 0,045

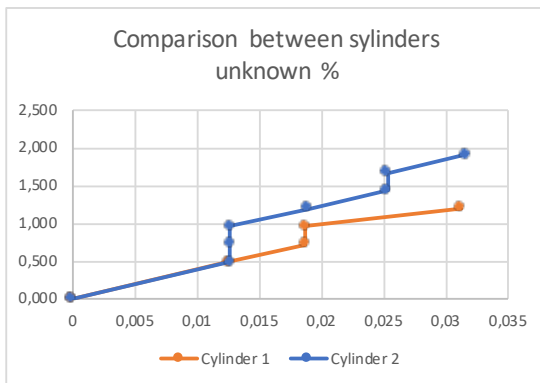
h [m]: 0,045

Area [m²]: 0,002025

Original height [mm]: 108

Mix unknown - Block						Crack load:			
Load		Result				m	F	P	σ
m	F	P	δ	ε [-]	σ	m	F	P	σ
20	196	1029,1	107	0,009259	0,508	85	835	4373,8	2,160
40	393	2058,3	107	0,009259	1,016				
60	589	3087,4	107	0,009259	1,525				
80	786	4116,5	106	0,018519	2,033				
100	982	5145,7	106	0,018519	2,541				
110	1080	5660,2	105	0,027778	2,795				
120	1178	6174,8	104	0,037037	3,049				
125	1228	6432,1	104	0,037037	3,176				
95	933	4888,4	100	0,074074	2,414				

At 95 kg applied load there is a 7 mm wide crack. A 5 mm compression mark after unloading.



Summary compressive strength blocks

Calculated characteristic compressive strength for blocks.

Specimen:	Compressive strength		
	P	sigma	f _c
10%	5918	2,92	1,95
15%	8748	4,32	2,88
20%	7719	3,81	2,54
Unknown%	6432	3,18	2,12

C

Test 3 in Sweden

Steel plate mass [kg]: 3,3
 Area cylinder [m²]: 0,003848
 Original height [mm]: 137,4

Cylinder 1					
Load		Result			
m [kg]	F [N]	P [N]	δ [mm]	ε [-]	σ [MPa]
3,3	32	169,8	137,4	0	0,044
8,3	82	427,1	137,4	0	0,111
13,3	131	684,4	137,4	0	0,178
18,3	180	941,7	137,4	0	0,245
23,3	229	1198,9	137,3	0,000728	0,312
28,3	278	1456,2	137,3	0,000728	0,378
33,3	327	1713,5	137,2	0,001456	0,445
38,3	376	1970,8	137,2	0,001456	0,512
43,3	425	2228,1	137,1	0,002183	0,579
48,3	474	2485,4	137,1	0,002183	0,646
53,3	523	2742,6	137	0,002911	0,713
58,3	573	2999,9	137	0,002911	0,780
63,3	622	3257,2	136,9	0,003639	0,846
68,3	671	3514,5	136,7	0,005095	0,913
73,3	720	3771,8	136,7	0,005095	0,980
78,3	769	4029,1	136,6	0,005822	1,047
83,3	818	4286,4	136,6	0,005822	1,114
88,3	867	4543,6	136,6	0,005822	1,181
93,3	916	4800,9	136,6	0,005822	1,247
98,3	965	5058,2	136,55	0,006186	1,314
103,3	1014	5315,5	136,5	0,00655	1,381
108,3	1064	5572,8	136,45	0,006914	1,448
113,3	1113	5830,1	136,3	0,008006	1,515
118,3	1162	6087,3	136,1	0,009461	1,582
123,3	1211	6344,6	136,1	0,009461	1,649
128,3	1260	6601,9	136,1	0,009461	1,715
133,3	1309	6859,2	136,1	0,009461	1,782
138,3	1358	7116,5	136,05	0,009825	1,849
143,3	1407	7373,8	135,8	0,011645	1,916
145,3	1427	7476,7	135	0,017467	1,943

Observations: Failure type, where does it fail, when does it crack?
 The least visible layers, bottom layer falls apart easily. Failure load: 142 kg. Crushing at the bottom + Shear failure. Reflection: Might have been slightly higher water content in the firstly rammed cylinder (nr 1) since the mixing was done by hand in a big bucket. This can have resulted in less visible layers and higher strength.

E-mod [MPa] 149,2681

Original height [mm]: 142,5

Cylinder 2					
Load		Result			
m [kg]	F [N]	P [N]	δ [mm]	ε [-]	σ [MPa]
3,3	32	169,8	142,5	0	0,044
8,3	82	427,1	142,5	0	0,111
13,3	131	684,4	142,5	0	0,178
18,3	180	941,7	142,4	0,000702	0,245
23,3	229	1198,9	142,4	0,000702	0,312
28,3	278	1456,2	142,4	0,000702	0,378
33,3	327	1713,5	142,35	0,001053	0,445
38,3	376	1970,8	142,35	0,001053	0,512
43,3	425	2228,1	142,3	0,001404	0,579
48,3	474	2485,4	142,25	0,001754	0,646
53,3	523	2742,6	142,25	0,001754	0,713
58,3	573	2999,9	142,2	0,002105	0,780
63,3	622	3257,2	142,2	0,002105	0,846
68,3	671	3514,5	142,2	0,002105	0,913
73,3	720	3771,8	142,2	0,002105	0,980
78,3	769	4029,1	142,15	0,002456	1,047
83,3	818	4286,4	142,15	0,002456	1,114
88,3	867	4543,6	142,15	0,002456	1,181
93,3	916	4800,9	142,1	0,002807	1,247
98,3	965	5058,2	142,1	0,002807	1,314
103,3	1014	5315,5	142,1	0,002807	1,381
108,3	1064	5572,8	142,1	0,002807	1,448
113,3	1113	5830,1	142,1	0,002807	1,515
118,3	1162	6087,3	142,05	0,003158	1,582
122,3	1201	6293,2	140	0,017544	1,635

Observations: Failure type, where does it fail, when does it crack?
 Visible layers. Failure on top under partly compressed area. Failure load 119 kg, but dropped slowly downwards compared to other cylinders.

E-mod [MPa] 444,5785

Original height [mm]: 141,6

Cylinder 3					
Load		Result			
m [kg]	F [N]	P [N]	δ [mm]	ε [-]	σ [MPa]
3,3	32	169,8	141,6	0	0,044
8,3	82	427,1	141,6	0	0,111
13,3	131	684,4	141,5	0,000706	0,178
18,3	180	941,7	141,4	0,001412	0,245
23,3	229	1198,9	141,3	0,002119	0,312
28,3	278	1456,2	141,1	0,003531	0,378
33,3	327	1713,5	141,05	0,003884	0,445
38,3	376	1970,8	141	0,004237	0,512
43,3	425	2228,1	140,8	0,00565	0,579
48,3	474	2485,4	140,75	0,006003	0,646
53,3	523	2742,6	140,6	0,007062	0,713
58,3	573	2999,9	140,45	0,008121	0,780
63,3	622	3257,2	140,2	0,009887	0,846
68,3	671	3514,5	140	0,011299	0,913
73,3	720	3771,8	139,75	0,013065	0,980
78,3	769	4029,1	139,55	0,014477	1,047
83,3	818	4286,4	139,5	0,014831	1,114
87,3	857	4492,2	139,3	0,016243	1,167

Observations: Failure type, where does it fail, when does it crack?
 Rather visible and equal layers. Not very big visible particles. Failure load at 84kg. Fails at top in the beginning, under a partly loaded area. When continued loading, it fails "from within" deflecting outwards all the way around.

E-mod [MPa] 66,2656

Original height [mm]: 144,2

Cylinder 4					
Load		Result			
m [kg]	F [N]	P [N]	δ [mm]	ε [-]	σ [MPa]
3,3	32	169,8	144,2	0	0,044
8,3	82	427,1	144,2	0	0,111
13,3	131	684,4	144,05	0,00104	0,178
18,3	180	941,7	143,9	0,00208	0,245
23,3	229	1198,9	143,8	0,002774	0,312
28,3	278	1456,2	143,6	0,004161	0,378
33,3	327	1713,5	143,5	0,004854	0,445
38,3	376	1970,8	143,45	0,005201	0,512
43,3	425	2228,1	143,4	0,005548	0,579
48,3	474	2485,4	143,4	0,005548	0,646
53,3	523	2742,6	143,4	0,005548	0,713
58,3	573	2999,9	143,35	0,005895	0,780
63,3	622	3257,2	143,3	0,006241	0,846
68,3	671	3514,5	143,25	0,006588	0,913
73,3	720	3771,8	143,25	0,006588	0,980
78,3	769	4029,1	143,15	0,007282	1,047
83,3	818	4286,4	143,1	0,007628	1,114
88,3	867	4543,6	143,05	0,007975	1,181
93,3	916	4800,9	143	0,008322	1,247
97,3	955	5006,7	143	0,008322	1,301

Observations: Failure type, where does it fail, when does it crack?
 Failure has already occurred between layers 2 and 3 before start of test. They were puzzled together and tested as the others. Failure load at 94 kg. Slightly unevenly loaded at top. Failure at top below the most loaded part.

E-mod [MPa] 146,9003

Original height [mm]: 150,8

Cylinder 5					
Load		Result			
m [kg]	F [N]	P [N]	δ [mm]	ϵ [-]	σ [MPa]
3,3	32	169,8	150,8	0	0,044
8,3	82	427,1	150,8	0	0,111
13,3	131	684,4	150,8	0	0,178
18,3	180	941,7	150,8	0	0,245
23,3	229	1198,9	150,8	0	0,312
28,3	278	1456,2	150,75	0,000332	0,378
33,3	327	1713,5	150,75	0,000332	0,445
38,3	376	1970,8	150,7	0,000663	0,512
43,3	425	2228,1	150,6	0,001326	0,579
48,3	474	2485,4	150,55	0,001658	0,646
53,3	523	2742,6	150,55	0,001658	0,713
58,3	573	2999,9	150,5	0,001989	0,780
63,3	622	3257,2	150,4	0,002653	0,846
68,3	671	3514,5	150,3	0,003316	0,913
73,3	720	3771,8	150,25	0,003647	0,980
78,3	769	4029,1	150,15	0,00431	1,047
83,3	818	4286,4	150,1	0,004642	1,114
88,3	867	4543,6	149,95	0,005637	1,181
93,3	916	4800,9	149,8	0,006631	1,247
98,3	965	5058,2	149,7	0,007294	1,314
101,3	995	5212,6	149,2	0,01061	1,354

Observations: Failure type, where does it fail, when does it crack?

Bottom layer falls apart easily (parts missing before test). Most visible layers of the cylinders. Also one "hole" at the top after a stone that fell off. Loaded at many small parts distributed under the loading plate. Failure load at 98 kg. Distributed crushing at the bottom of the cylinder

E-mod [MPa] 155,8061

Original height [mm]: 144,4

Cylinder 6					
Load		Result			
m [kg]	F [N]	P [N]	δ [mm]	ϵ [-]	σ [MPa]
3,3	32	169,8	144,4	0	0,044
8,3	82	427,1	144,4	0	0,111
13,3	131	684,4	144,3	0,000693	0,178
18,3	180	941,7	144,3	0,000693	0,245
23,3	229	1198,9	144,1	0,002078	0,312
28,3	278	1456,2	144	0,00277	0,378
33,3	327	1713,5	143,7	0,004848	0,445
38,3	376	1970,8	143,5	0,006233	0,512
43,3	425	2228,1	143,4	0,006925	0,579
48,3	474	2485,4	143,4	0,006925	0,646
53,3	523	2742,6	143,3	0,007618	0,713
58,3	573	2999,9	143,1	0,009003	0,780
63,3	622	3257,2	143	0,009695	0,846
68,3	671	3514,5	142,85	0,010734	0,913
73,3	720	3771,8	142,6	0,012465	0,980
75,3	739	3874,7	142	0,01662	1,007
91,3	897	4698,0	141,7	0,018698	1,221
98,3	965	5058,2	141,5	0,020083	1,314
113,3	1113	5830,1	141	0,023546	1,515

Observations: Failure type, where does it fail, when does it crack?

Bottom layer falls apart easily, parts missing at the beginning of the test. Very uneven top surface, three significant compression points from stones at the top. Failure load at 110 kg. The whole cylinder pulverized.

E-mod [MPa] 58,61178

Original height [mm]: 144

Cylinder 7					
Load		Result			
m [kg]	F [N]	P [N]	δ [mm]	ϵ [-]	σ [MPa]
3,3	32	169,8	144	0	0,044
8,3	82	427,1	144	0	0,111
13,3	131	684,4	144	0	0,178
18,3	180	941,7	144	0	0,245
23,3	229	1198,9	144	0	0,312
28,3	278	1456,2	144	0	0,378
33,3	327	1713,5	144	0	0,445
38,3	376	1970,8	144	0	0,512
43,3	425	2228,1	144	0	0,579
48,3	474	2485,4	144	0	0,646
53,3	523	2742,6	144	0	0,713
58,3	573	2999,9	144	0	0,780
63,3	622	3257,2	144	0	0,846
68,3	671	3514,5	144	0	0,913
73,3	720	3771,8	143,9	0,000694	0,980
78,3	769	4029,1	143,85	0,001042	1,047
83,3	818	4286,4	143,8	0,001389	1,114
88,3	867	4543,6	143,75	0,001736	1,181
93,3	916	4800,9	143,7	0,002083	1,247
98,3	965	5058,2	143,7	0,002083	1,314
103,3	1014	5315,5	143,7	0,002083	1,381
108,3	1064	5572,8	143,65	0,002431	1,448
113,3	1113	5830,1	143,6	0,002778	1,515
118,3	1162	6087,3	143,6	0,002778	1,582
119,3	1172	6138,8	143,6	0,002778	1,595

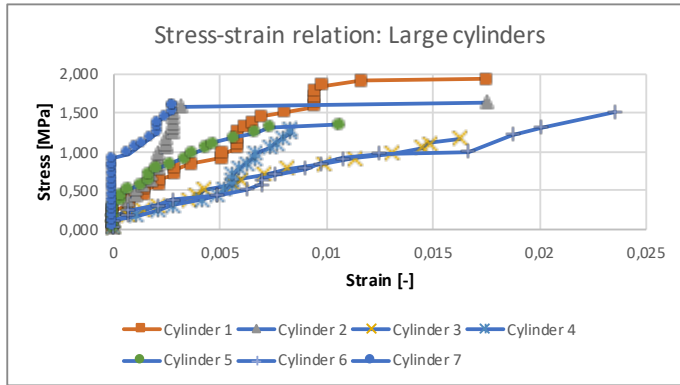
Observations: Failure type, where does it fail, when does it crack?

Rather even top surface for loading. Not many visible large particles. Failure load 116 kg. Total crushing from the bottom. No strain was seen until it was loaded quite far. Crack sounds could be heard while loading with no change in strain. This might be because the load was applied unevenly and the steel plate therefore tilted in one direction, which could not be measured from the measuring point.

E-mod [MPa] 505,4156

Summary

	Failure loads:						Elastic modulus:		Common observations for all the cylinders:
	P [kN]	σ [MPa]	f_a [MPa]	$(x\text{-sum})^2$	stan.dev	f_c [MPa]	E [MPa]	E_m [MPa]	
Cylinder 1	7,48	1,94		0,19			149		All cylinders have visible layers, some contains more larger particles than others. Bottom layer quite thick compared to the other layers (slightly harder to ram + probably extra soil). Weight of steel plate is added to all the numbers.
Cylinder 2	6,29	1,64		0,02			445		
Cylinder 3	4,49	1,17		0,11			66		
Cylinder 4	5,01	1,30	1,50	0,04	0,2566	1,08	147	218	
Cylinder 5	5,21	1,35		0,02			156		
Cylinder 6	5,83	1,51		0,00			59		
Cylinder 7	6,14	1,60		0,01			505		



D

Compression tests in The Gambia

Soil from rammed earth constructor

Bought soil from a rammed earth entrepreneur. Cylinders rammed 16th of April at 7 pm.

Area cylinder [m²]: 0,003848

		Cylinder 1				Cylinder 2				Cylinder 3			
		Load		Result		Load		Result		Load		Result	
		m [kg]	F [N]	P [N]	σ [MPa]	m [kg]	F [N]	P [N]	σ [MPa]	m [kg]	F [N]	P [N]	σ [MPa]
Cracking load:		14	137	720,4	0,187	12	118	617,5	0,160	72	707	3704,9	0,963
Failure load:		50	491	2572,8	0,669	39	383	2006,8	0,521	78	766	4013,6	1,043
		Failure mode: Flaky failure				Failure mode: Tile broke on top - one big crack below it. Disregarded result				Failure mode: Shear failure, crack at bottom			

		Cylinder 4				Cylinder 5				Cylinder 6			
		Load		Result		Load		Result		Load		Result	
		m [kg]	F [N]	P [N]	σ [MPa]	m [kg]	F [N]	P [N]	σ [MPa]	m [kg]	F [N]	P [N]	σ [MPa]
Cracking load:		66	648	3396,1	0,882	55	540	2830,1	0,735	47	462	2418,5	0,628
Failure load:		74	727	3807,8	0,989	72	707	3704,9	0,963	78	766	4013,6	1,043
		Failure mode: Brittle failure, crack going all the way through the cylinder				Failure mode: Flaky failure				Failure mode: Brittle failure, flaky failure			

		Cylinder 7				Cylinder 8			
		Load		Result		Load		Result	
		m [kg]	F [N]	P [N]	σ [MPa]	m [kg]	F [N]	P [N]	σ [MPa]
Cracking load:		48	471	2469,9	0,642	55	540	2830,1	0,735
Failure load:		55	540	2830,1	0,735	68	668	3499,1	0,909
		Failure mode: Crushing on top				Failure mode: Crushing on top			

Failure loads for soil from rammed earth constructor:						
	P [kN]	σ [MPa]	fa [MPa]	(x-sum) ²	stan.dev	fc [MPa]
Cylinder 1	2,57	0,67		0,06		
Cylinder 2	0,00	0,00		0,00		
Cylinder 3	4,01	1,04		0,02		
Cylinder 4	3,81	0,99	0,91	0,01	0,1490	0,66
Cylinder 5	3,70	0,96		0,00		
Cylinder 6	4,01	1,04		0,02		
Cylinder 7	2,83	0,74		0,03		
Cylinder 8	3,50	0,91		0,00		

Road soil

Soil taken from road construction. Cylinders rammed 25th of April at 7 pm.

Area cylinder [m²]: 0,003848

		Cylinder 1				Cylinder 2				Cylinder 3			
		Load		Result		Load		Result		Load		Result	
		m [kg]	F [N]	P [N]	σ [MPa]	m [kg]	F [N]	P [N]	σ [MPa]	m [kg]	F [N]	P [N]	σ [MPa]
Cracking load:		27	265	1389,3	0,361	16	157	823,3	0,214	51	501	2624,3	0,682
Failure load:		30	295	1543,7	0,401	36	354	1852,4	0,481	64	628	3293,2	0,856
		Failure mode: Crushing				Failure mode: Crushing on top and shear				Failure mode: Shear failure			

		Cylinder 4				Cylinder 5			
		Load		Result		Load		Result	
		m [kg]	F [N]	P [N]	σ [MPa]	m [kg]	F [N]	P [N]	σ [MPa]
Cracking load:		38	373	1955,4	0,508	23	226	1183,5	0,308
Failure load:		40	393	2058,3	0,535	33	324	1698,1	0,441
		Failure mode: Shear failure				Failure mode: Shear failure			

Failure loads for road soil:						
	P [kN]	σ [MPa]	fa [MPa]	(x-sum) ²	stan.dev	fc [MPa]
Cylinder 1	1,54	0,40		0,020		
Cylinder 2	1,85	0,48		0,004		
Cylinder 3	3,29	0,86	0,54	0,098	0,1818	0,24
Cylinder 4	2,06	0,53		0,000		
Cylinder 5	1,70	0,44		0,010		

Soil from rammed earth constructor with 5% cement

Soil bought from rammed earth constructor. 5% cement added. Cylinders rammed 25th of April at 7 pm.

Area cylinder [m²]: 0,003848

	Cylinder 1				Cylinder 2				Cylinder 3			
	Load		Result		Load		Result		Load		Result	
	m [kg]	F [N]	P [N]	σ [MPa]	m [kg]	F [N]	P [N]	σ [MPa]	m [kg]	F [N]	P [N]	σ [MPa]
Cracking load:	46	452	2367,0	0,615	41	403	2109,7	0,548	48	471	2469,9	0,642
Failure load:	64	628	3293,2	0,856	80	786	4116,5	1,070	55	540	2830,1	0,735
	Failure mode: Ductile failure, several bigger parts fell off before collapse				Failure mode: Ductile failure, crushing on top				Failure mode: Ductile shear failure			

	Cylinder 4				Cylinder 5				Cylinder 6			
	Load		Result		Load		Result		Load		Result	
	m [kg]	F [N]	P [N]	σ [MPa]	m [kg]	F [N]	P [N]	σ [MPa]	m [kg]	F [N]	P [N]	σ [MPa]
Cracking load:	58	570	2984,5	0,776	64	628	3293,2	0,856	42	412	2161,2	0,562
Failure load:	63	619	3241,8	0,842	95	933	4888,4	1,270	52	511	2675,8	0,695
	Failure mode: Crushing at the bottom				Failure mode: Crushing				Failure mode: Shear failure with multiple cracks			

Failure loads for soil with 5% cement:						
	P [kN]	σ [MPa]	fa [MPa]	(x-sum) ²	stan.dev	fc [MPa]
Cylinder 1	3,29	0,86		0,00		
Cylinder 2	4,12	1,07		0,03		
Cylinder 3	2,83	0,74		0,03		
Cylinder 4	3,24	0,84	0,91	0,00	0,2188	0,55
Cylinder 5	4,89	1,27		0,13		
Cylinder 6	2,68	0,70		0,05		

Road soil with varying drying time

Soil taken from road construction. Cylinder 1-5 were rammed 27th of April at 4 pm and cylinder 6-7 were rammed the 25th of April at 7 pm. All cylinders were tested in the morning around 9 am.

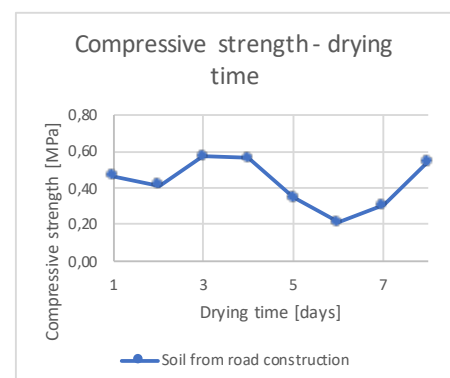
Area cylinder [m²]: 0,003848

	Day 1				Day 2				Day 3			
	Load		Result		Load		Result		Load		Result	
	m [kg]	F [N]	P [N]	σ [MPa]	m [kg]	F [N]	P [N]	σ [MPa]	m [kg]	F [N]	P [N]	σ [MPa]
Cracking load:	31	304	1595,2	0,414	0	0	0,0	0,000	0	0	0,0	0,000
Failure load:	35	344	1801,0	0,468	31	304	1595,2	0,414	43	422	2212,6	0,575
	Failure mode: Shear failure				Failure mode: Brittle failure. Shear plane along large part of the cylinder. No visible cracks.				Failure mode: Very brittle failure, crushing in second layer. No visible cracks.			

	Day 4				Day 5				Day 6			
	Load		Result		Load		Result		Load		Result	
	m [kg]	F [N]	P [N]	σ [MPa]	m [kg]	F [N]	P [N]	σ [MPa]	m [kg]	F [N]	P [N]	σ [MPa]
Cracking load:	29	285	1492,2	0,388	22	216	1132,0	0,294	7	69	360,2	0,094
Failure load:	42	412	2161,2	0,562	26	255	1337,9	0,348	16	157	823,3	0,214
	Failure mode: Crushing on top and then shear failure through bigger part of the specimen.				Failure mode: Crushing in the middle layer				Failure mode: Shear + crushing			

	Day 7			
	Load		Result	
	m [kg]	F [N]	P [N]	σ [MPa]
Cracking load:	19	187	977,7	0,254
Failure load:	23	226	1183,5	0,308
	Failure mode: Shear failure			

Failure loads for road soil with varying drying time:						
	P [kN]	σ [MPa]	fa [MPa]	(x-sum) ²	stan.dev	fc [MPa]
Day 1	1,80	0,47		0,00		
Day 2	1,60	0,41		0,00		
Day 3	2,21	0,57		0,02		
Day 4	2,16	0,56		0,02		
Day 5	1,34	0,35	0,43	0,01	0,1316	0,21
Day 6	0,82	0,21		0,05		
Day 7	1,18	0,31		0,01		
Day 8-ave		0,54		0,01		



E

Prototype calculations

Prototype calculations

In this appendix, calculations of the prototype are presented. The calculations include control of compressive stress in the highest loaded CEB, moment and shear capacity in the supporting beam in ULS, and tension capacity in reinforcement bars acting as tension ties.

Input

Vault geometry:

```
s = 3;           % [m]
h = s/10;       % [m]
d = 1.5;        % [m]

t_rib = 0.04;   % [m]
c_rib = 0.75;   % [m] cc between ribs

t_CEB = 0.06;   % [m]
l_CEB = 2*sqrt((s/2)^2+(h*1.5)^2); % Assume triangular shape

t_fill = (h-t_CEB)/2; % [m]
t_surf = 0.05;  % [m]
```

Assumed material properties:

```
density_CEB = 2013; % [kg/m3] Measured in The Gambia
density_fill = 250; % [kg/m3] LECA
density_concrete = 2400; % [kg/m3]

fyk_rebar = 500E6; % [Pa]
Es = 200E9; % [Pa]

fck = 20E6; % [Pa]
```

Loads:

```
% Self-weight slab
g =
(t_CEB*l_CEB/s*density_CEB+t_fill*density_fill+t_surf*density_concrete)*d*9.82;
% [N/m]

% Self-weight concrete ribs
n_rib = ceil(d/c_rib)+1; % Number of ribs
g_rib = t_fill*t_rib*density_concrete*9.82*(n_rib/d); % [N/m] Smear out
```

```

% Live load for school (Swedish Standards Institute, 2008)
q = 3000*d;

% Total load
w = g+g_rib+q;

% Safety factor ("Factors of Safety", n.d.)
Global_safety = 2.5;

```

Reaction forces:

```

% Horizontal reaction force [N] (Block et al., 2010)
H = w*s^2/(8*h)

```

H = 3.2974e+04

```

% Vertical reaction force [N]
V = w*s/2

```

V = 1.3190e+04

```

% Resultant [N]
F = sqrt(H^2+V^2)

```

F = 3.5515e+04

Control of compressive stress in the CEB

The compressive stress in the heaviest loaded CEB in the vault should not exceed 7 MPa which is the compressive capacity of the CEB according to Mr. Jallow.

```

sigma_CEB = F/(t_CEB*d);
if sigma_CEB<=7E6
    Check_CEB = 1
else
    Check_CEB = 0
end

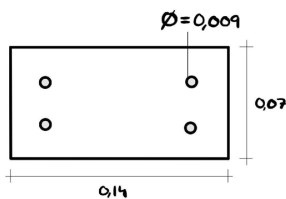
```

Check_CEB = 1

The compressive stress is below compressive strength. OK.

Ring beam

The ring beam will be cast inside U-blocks with the dimensions 140x70 mm. The ring beam is therefore assumed to have these dimensions. Field studies show that it is common to reinforce with one rebar in each corner held in place with stirrups. Therefore, four reinforcement bars are assumed, one in each corner. The cross-section design can be seen in the figure below. All dimensions in [m].



Moment capacity

The moment capacity of the beam is calculated to ensure sufficient moment strength in ULS.

Beam geometry:

```
% Geometry
w_beam = 0.14;
h_beam = 0.7;
l_beam = d;
bar_diam_beam_top = 0.009;
bar_diam_beam = 0.009;

% Reinforcement top
n_bar_beam_top = 2;
Asi_beam_top = (pi*bar_diam_beam_top^2)/4;
As_beam_top = Asi_beam_top*n_bar_beam_top;

% Reinforcement bottom
n_bar_beam = 2;
Asi_beam = (pi*bar_diam_beam^2)/4;
As_beam = Asi_beam*n_bar_beam;

% Dist from top to c.g. rebars
ec = 0.02; % Concrete coverage
d_lev_beam_top = ec+bar_diam_beam_top/2;
d_lev_beam = w_beam-(ec+bar_diam_beam/2);
```

Applied moment:

```
M_Ed_beam = (H/d)*l_beam^2/8*Global_safety
```

```
M_Ed_beam = 1.5457e+04
```

Initial assumption: all reinforcement yield. The cross-section is assumed to be uncracked, hence, the neutral layer is in the middle.

```
epsilon_cu = 3.5E-3;
epsilon_sy = fyk_rebar/Es;
%{
x_beam = w_beam/2 % Symmetric cross-section without cracks, natural layer in
the middle

% Check that the bottom reinforcement yield
epsilon_sy
epsilon_s = (d_lev_beam-x_beam)/x_beam*epsilon_cu
if epsilon_s>=epsilon_sy
    Check_yield = 1
else
    Check_yield = 0
end

% Check that the top reinforcement yield
epsilon_s_top = (x_beam-d_lev_beam_top)/x_beam*epsilon_cu;
if epsilon_s_top>=epsilon_sy
    Check_yield_top = 1
else
    Check_yield_top = 0
end
%}
```

Neither the top nor bottom reinforcement yields. **New assumption:** none of the reinforcement yield.

```
x_beam = w_beam/2; % Symmetric cross-section without cracks, natural layer in
the middle

% Check that the bottom reinforcement does not yield
epsilon_s = (d_lev_beam-x_beam)/x_beam*epsilon_cu;
if epsilon_s<=epsilon_sy
    Check_yield = 1
else
    Check_yield = 0
end

Check_yield = 1
```

```

% Check that the top reinforcement does not yield
epsilon_s_top = (x_beam-d_lev_beam_top)/x_beam*epsilon_cu;
if epsilon_s_top<=epsilon_sy
    Check_yield_top = 1
else
    Check_yield_top = 0
end

```

```
Check_yield_top = 1
```

None of the reinforcement yield. OK. Below the moment capacity of the cross-section is calculated.

```

M_Rd_beam = fck*h_beam*0.8*x_beam*(d_lev_beam-
(0.8*x_beam/2))+Es*epsilon_s_top*As_beam_top*(d_lev_beam-d_lev_beam_top);
ut_beam = vpa(M_Ed_beam/M_Rd_beam)

```

```

ut_beam =
0.20924792336597358710648109081376

```

The utilization ratio is sufficient and the chosen design has enough moment capacity.

Shear capacity

Below the required size and spacing of stirrups is calculated to provide sufficient shear capacity in ULS.

```

% Applied shear
V_Ed = (H/d)*l_beam/2*Global_safety;

% Check crushing of web
v = 0.6*(1-(fck*10^-6/250));
if V_Ed<=0.5*v*fck*h_beam*d_lev_beam
    Check_crushing_web = 1
else
    Check_crushing_web = 0
end

```

```
Check_crushing_web = 1
```

Crushing is not a problem. Check if stirrups are required.

```

% Shear force 0.9d from support
V_Ed_check = V_Ed-(H/d)*0.9*d_lev_beam;

% Reduced V_Ed
V_Ed_red = V_Ed_check-((2*d_lev_beam-(0.9*d_lev_beam))^2/(4*d_lev_beam)*(H/d));

```

```

% Shear capacity
C_Rd_c = 0.18;
%k = 1+sqrt(0.2/d_lev_beam) % <2
k = 2;
%rho_l = As_beam/(h_beam*d_lev_beam) % <0.02
rho_l = 0.02;

V_Rd_c = C_Rd_c*k*(100*rho_l*fck*10^-6)^(1/3)*10^6*h_beam*d_lev_beam; % [Pa]
if V_Ed_red<=V_Rd_c
    Check_stir_needed = 1
else
    Check_stir_needed = 0
end

```

Check_stir_needed = 1

No stirrups are required.

Tension ties

The tension between the two ring beams is carried by reinforcement bars on each side of the vault. Below the required number of rebars is calculated.

```

Area_steel_rod = (H/2)/fyk_rebar;
Area_steel_rod/Asi_beam;
n_steel_rod = ceil(Area_steel_rod/Asi_beam)

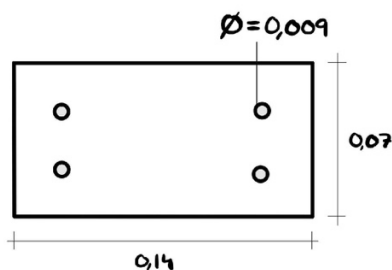
```

n_steel_rod = 1

One rebar is sufficient to carry the tension. Notice: anchorage of the tension rod must be made carefully.

Final design

The final design can be seen in the figure below. Stirrups will be added to hold the rebars in place. All dimensions in [m].



F

Implementation calculations

Implementation EB-Elementary

In this Appendix, the floor slab evaluated in the workshop is adapted to a rammed earth school and dimensioned for application in an EB-Elementary. Firstly, the wall thickness on the 2nd floor is estimated. Further, the wall thickness on the 1st floor is calculated. The found wall thickness is to set the dimensions of the ring beam.

Input

Vault geometry:

```
clear all
clc

s = 7.5;           % [m]
h = s/10;         % [m]
d = 1;           % [m]

t_rib = 0.04;     % [m]
c_rib = 0.75;     % [m] (c-c between ribs)

t_CEB = 0.09;     % [m] Updated after workshop
l_CEB = 2*sqrt((s/2)^2+(h*1.5)^2); % Assume triangular shape

t_fill = (h-t_CEB)/2; % [m]
t_surf = 0.05;    % [m]
room_height = 2.5; % [m] Height up to the beginning of the vault

% Material properties
density_CEB = 2013; % [kg/m3]
density_rammed_earth = 2250; % [kg/m3]
density_fill = 30; % [kg/m3] EPS (Expanded Polystyrene)
density_concrete = 2400; % [kg/m3]

fyk_rebar = 500E6;
Es = 200E9;

fck = 20E6; % Assume C20/25
```

Loads:

```
% Self-weight slab
g =
(t_CEB*l_CEB/s*density_CEB+t_fill*density_fill+t_surf*density_concrete)*d*9.82;
% [N/m]
```

```

% Self-weight concrete ribs
n_rib = ceil(d/c_rib)+1; % Needed number of ribs
g_rib = t_fill*t_rib*density_concrete*9.82*(n_rib/d); % [N/m] Smearred out

% Live load for school (Swedish Standards Institute, 2008)
q = 3000*d; % [N/m] Category C1 according to Actions on structures

% Total load
w = g+g_rib+q;

% Safety factor ("Factors of Safety", n.d.)
Global_safety = 2.5;

```

Reaction forces:

```

% Horizontal reaction force [N] (Block et al., 2010)
H = w*s^2/(8*h) % [N]

```

H = 6.6247e+04

```

% Vertical reaction force
V = w*s/2 % [N]

```

V = 2.6499e+04

```

% Resultant
F = sqrt(H^2+V^2) % [N]

```

F = 7.1350e+04

Control of compressive stress in the CEB

The compressive stress in the heaviest loaded CEB in the vault should not exceed 7 MPa which is the compressive capacity of the CEB according to Mr. Jallow.

```

sigma_CEB = F/(t_CEB*d);
if sigma_CEB<=7E6
    Check_CEB = 1
else
    Check_CEB = 0
end

```

Check_CEB = 1

The compressive stress is below compressive strength. OK.

Wall thickness - 2nd floor

The wall thickness is calculated according to the African harmonized standard. The thickness of the wall should not be less than 300 [mm] and the slenderness ratio should not be less than 1:8. It is then controlled so that the wall can carry the weight from the roof as well as the self-weight of the wall.

```
sigma_rammed_earth = 2.0E6;           % [Pa] Assumed compressive strength of
rammed earth
t_wall = room_height/8;                % Above 0.3 [m] OK
t_wall = 0.32;                          % Chosen

% Calculated erosion
calc_out_2nd = 0.02;
calc_in_2nd = 0.01;
t_wall_2nd = t_wall+calc_out_2nd+calc_in_2nd

t_wall_2nd = 0.3500
```

```
N_Rd = sigma_rammed_earth*t_wall;     % Compressive capacity

% Control that the wall can carry the weight
Thatched_roof_steel = 40*9.82; % [N/m2]
roof = 40*9.82*s/2; % [N/m] Assume roof weight 40 [kg/m2]
wall_2nd = t_wall_2nd*room_height*density_rammed_earth*9.82; % [N/m]

N_Ed_2nd = (roof+wall_2nd)*Global_safety; % [N/m]
ut_wall_2nd = N_Ed_2nd/N_Rd

ut_wall_2nd = 0.0813
```

The capacity is OK.

Wall thickness - 1st floor

Control is done to assure that the wall can carry the weight from the roof, the wall on the 2nd floor, and the slab.

```
% Calculated erosion
calc_out_1st = 0.05;
calc_in_1st = 0.01;
t_wall_1st = t_wall+calc_out_1st+calc_in_1st

t_wall_1st = 0.3800

wall_1st = t_wall_1st*room_height*density_rammed_earth*9.82; % [N/m]

N_Ed_1st = (roof+wall_1st+wall_2nd+V/d)*Global_safety; % [N/m]
```

```
ut_wall_1st = N_Ed_1st/N_Rd
```

```
ut_wall_1st = 0.2668
```

The capacity is OK. and the ringbeam can be the same thickness as the wall.

Ring beam

The ring beam will be cast with the same formwork as the rammed earth wall and therefore has the same width as the wall.

```
% Geometry
w_beam = t_wall_1st;
h_beam = 0.3;    % Iterated
l_beam = 3;     % Iterated

% Reinforcement top
bar_diam_beam_top = 0.009; % Iterated
n_bar_beam_top = 2;
Asi_beam_top = (pi*bar_diam_beam_top^2)/4;
As_beam_top = Asi_beam_top*n_bar_beam_top;

% Reinforcement bottom
bar_diam_beam = 0.018;    % Iterated
n_bar_beam = 6;          % Iterated
Asi_beam = (pi*bar_diam_beam^2)/4;
As_beam = Asi_beam*n_bar_beam;

% Dist top to c.g. rebars
ec = 0.03;    % Concrete coverage
cc_beam = (h_beam-ec*2-bar_diam_beam*n_bar_beam)/(n_bar_beam-1);
d_lev_beam_top = ec+bar_diam_beam_top/2;
d_lev_beam = w_beam-(ec+bar_diam_beam/2);
```

Applied moment:

```
M_Ed_beam = (H/d)*l_beam^2/8*Global_safety
```

```
M_Ed_beam = 1.8632e+05
```

Initial assumption: all reinforcement yields

```
epsilon_cu = 3.5E-3;
epsilon_sy = fyk_rebar/Es;
```

```
x_beam = (fyk_rebar*As_beam-fyk_rebar*As_beam_top)/(0.8*h_beam*fck)
```

```
x_beam = 0.1458
```

```

epsilon_s = (d_lev_beam-x_beam)/x_beam*epsilon_cu;
if epsilon_s>=epsilon_sy
    Check_yield = 1
else
    Check_yield = 0
end

```

```

    Check_yield = 1

```

```

epsilon_s_top = (x_beam-d_lev_beam_top)/x_beam*epsilon_cu;
if epsilon_s_top>=epsilon_sy
    Check_yield_top = 1
else
    Check_yield_top = 0
end

```

```

    Check_yield_top = 1

```

```

% Control of moment capacity
M_Rd_beam = fck*h_beam*0.8*x_beam*(d_lev_beam-
(0.8*x_beam/2))+Es*epsilon_sy*As_beam_top*(d_lev_beam-d_lev_beam_top)

```

```

M_Rd_beam = 2.1732e+05

```

```

ut_beam = M_Ed_beam/M_Rd_beam

```

```

    ut_beam = 0.8574

```

The top reinforcement does not yield. **New assumption:** top reinforcement does not yield but the bottom does.

```

%{
syms x
eqn = fck*h_beam*0.8*x+Es*(x-d_lev_beam_top)/x*epsilon_cu*As_beam_top ==
fyk_rebar*As_beam;
x_beam = vpasolve(eqn,x)
x_beam = x_beam(2)

% New controll to see that lower yields and upper don't
epsilon_s = (d_lev_beam-x_beam)/x_beam*epsilon_cu;
if epsilon_s>=epsilon_sy
    Check_yield = 1
else
    Check_yield = 0
end

epsilon_s_top = (x_beam-d_lev_beam_top)/x_beam*epsilon_cu;
if epsilon_s_top<=epsilon_sy

```

```

    Check_yield_top = 1
else
    Check_yield_top = 0
end

% Control of moment capacity
M_Rd_beam = fck*h_beam*0.8*x_beam*(d_lev_beam-
(0.8*x_beam/2))+Es*epsilon_s_top*As_beam_top*(d_lev_beam-d_lev_beam_top)
ut_beam = vpa(M_Ed_beam/M_Rd_beam)
%}

```

The utilization ratio is sufficient and the chosen design has enough moment capacity.

Shear capacity

Below the required size and spacing of stirrups is calculated to provide sufficient shear capacity in ULS.

```

% Applied shear
V_Ed = (H/d)*I_beam/2*Global_safety;

% Check crushing of web
v = 0.6*(1-(fck*10^-6/250));
if V_Ed<=0.5*v*fck*h_beam*d_lev_beam
    Check_crushing_web = 1
else
    Check_crushing_web = 0
end

```

```

    Check_crushing_web = 1

```

Crushing is not a problem. Check if stirrups are required.

```

% Shear force 0.9d from support
V_Ed_check = V_Ed-(H/d)*0.9*d_lev_beam;

% Reduced V_Ed
V_Ed_red = V_Ed_check-((2*d_lev_beam-(0.9*d_lev_beam))^2/(4*d_lev_beam)*(H/d));

% Shear capacity
C_Rd_c = 0.18;
%k = 1+sqrt(0.2/d_lev_beam) % <2
k = 2;
%rho_l = As_beam/(h_beam*d_lev_beam) % <0.02
rho_l = 0.02;

V_Rd_c = C_Rd_c*k*(100*rho_l*fck*10^-6)^(1/3)*10^6*h_beam*d_lev_beam; % [Pa]

```

```

if V_Ed_red<=V_Rd_c
    Check_stir_needed = 1
else
    Check_stir_needed = 0
end

```

Check_stir_needed = 0

Stirrups are required. Choose the angle of compression to 35 degrees and control crushing in the inclined compression zone.

```

theta = 35;
x2 = cotd(theta)*0.9*d_lev_beam;
V_Ed_check2 = V_Ed-(H/d)*x2;

% Reduced V_Ed
V_Ed_red2 = V_Ed_check2-((2*d_lev_beam-(x2))^2/(4*d_lev_beam)*(H/d));

% Crushing diagonal compression zone
z = 0.9*d_lev_beam;
V_Rd_max = h_beam*z*v*fck/(cotd(theta)+tand(theta));

% Control crushing diagonal compression
if V_Ed<=V_Rd_max
    Check_crushing_diagonal = 1
else
    Check_crushing_diagonal = 0
end

```

Check_crushing_diagonal = 1

The capacity is sufficient. Dimensioning of stirrups.

```

V_Rd_s = V_Ed_red2;
Asw = 2*pi*0.009^2/4;    % Choose 9 [mm] stirrups
s = (z*cotd(theta)*fyk_rebar*Asw)/V_Rd_s

```

s = 0.1288

s is the required spacing between stirrups. According to Eurocode, there is a minimum spacing and amount of stirrups which is checked below.

```

% Check the maximum cc between stirrups
s_l_max = 0.75*d_lev_beam;
if s>=s_l_max
    s = s_l_max
else
    s = s
end

```

s = 0.1288

```

% Check the minimum amount of stirrups
rho_w = Asw/(s*h_beam);
if rho_w>=0.08*sqrt(fck*10^-6)/(fyk_rebar*10^-6)
    Check_min_stir = 1
else
    Check_min_stir = 0
end

```

Check_min_stir = 1

The calculated s is enough.

Tension ties

The tension between the two ring beams is carried by reinforcement bars on each side of the vault. Below the required number of rebars is calculated.

```

Area_steel_rod = (H/2)/fyk_rebar;
diam = 2*sqrt(Area_steel_rod/pi)

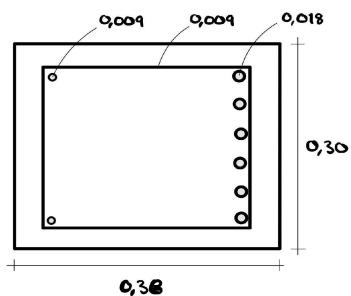
```

diam = 0.0092

A steel rod with a diameter of 10 mm is required.

Final design

The final design can be seen in the figure below. All dimensions in [m].



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