Structural Analysis of adobe bricks

Analysing the Difference in Compression of handmade unburned adobe bricks with and without the Addition of reinforcing materials.

AR3B011 EARTHY (2019/20 Q1) **Earthy, Material testing**

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Key words - *Adobe Bricks, Handmade, Adobe reinforcement, compression testing, straw, eggshells, lime, wooden ash, woodchips, sand, starch.*

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Preface

The following research report was a laboratory experiment conducted on October 2nd, 2019 for the course AR3B011 EARTHY (2019/20 Q1) for the master track Building Technology of the faculty of Architecture, Urbanism and Building Sciences. The tested specimens where hand made during a workshop on the 25th September 2019, at the Model Hall of the faculty of Architecture.

This laboratory experiment was conducted at the 3ME lab at the Faculty of Mechanical Maritime and Materials building at the Delft University of Technology. It was performed under the supervision of Dr.ir. Fred A. Veer, to whom we would like to thank for his time and effort.

Abstract

Handcrafted adobe bricks are still one of the most used building materials in the World. Due to inconsistencies during their production the compressive strength varies largely. To use adobe bricks in compression only structures in a refugee camp in Jordan it is required to know the compressive strength they can withstand. Since adobe performs bad in tension, we tried to add reinforcing materials that are locally available. Later we checked the performance of the created composite materials compared with a standard clay and sand mixture.
The question is: What added material or production technique increases the compressional strength of the bricks the most. By performing a compressional load test on the previously mentioned different adobe bricks we are able the analyse the influence of the different additives on the compression strength.

1 Introduction

EARTHY is a master's level design studio with the aim of designing and engineering earthen buildings, adobe buildings, intended for displaced communities. Our goal is to design buildings that can be ideally built by their prospective inhabitants. Earthen buildings are virtually 100% recyclable and, compared to tents, they offer much more comfort. The use of earthy materials necessitates the knowledge of complex geometry e.g. in designing and technical drawing of vaults, domes and arches in optimal shapes. To construct these buildings, we are researching and testing different mixtures of clay. The structural properties of those adobe bricks will be analysed in the report. (earthy course brief)

2 Methodology

2.1 Problem Statement

Circularity is the next challenging swift in the building industry. Clay is an excellent material for circular buildings since it is completely recyclable. Unfortunately, clay performs structurally bad compared to conventional building materials such as concrete, timber or steel. To make clay stronger in under tension and therefore also stronger under compression we tried to find different material combination. The material we choose to add to strengthen the clay mixture are all comparable easy to access locally and cheap or waste products. The increased performance of the tested clay bricks should help reviving clay as a building material not only for expelled people.

2.2 Research Objective

The research objective for this experiment is to identify the difference in performance of various clay mixtures and with or without the additional material as a reinforcement. By measuring and analysing these differences, we can statistically evaluate the performance of each sample by means of compressional strength.

2.3 Main Research Question

Which clay mixture and material combination has the highest compressional strength?

2.4 Testing Method

Since the adobe bricks where hand crafted and some of the added materials where cross contaminated (ex: wooden ash still contains small parts of charcoal) the experiment is not 100% repeatable. But through measurement and documentation we took care to make it as repeatable as possible.
A week before the brick testing took place we produced the different specimens in an adobe making workshop (25.10.19). We mixed the standard mix together and added later materials for reinforcement. Later the mixture was put into moulds (small and big).
After letting the clay bricks dry for one week the testing took place.
A compression test with an automatic digital compression testing machine (max. strength 100 kN) was performed to estimate the strength of the adobe bricks. Each brick was photographed before and after the brick testing, the yield strength was written down manually.

2.5 What mixtures and brick sizes were tested and why.

In this experiment the variable of interest is which mixture of clay, sand, water and additives preforms the best under compressive strength.

We made and tested 9 different mixtures

1. **Standard mixture** (small brick): S1s, S2s, S3s, S4s, S5s
2. **Standard mixture + Wood chips** (small brick): SW1s, SW2s, SW3s
3. **Standard mixture + Ash** (small brick): SA1s, SA2s, SA3s

4. **Standard mixture + Ash + Lime (calcium hydroxide)** (small bricks): SAL1s, SAL2s, SAL3s, SAL4s, SAL5s
5. **Standard mixture** (bigger brick): S1b, S2b, S3b, S4b, S5b
6. **Standard mixture + Straw ,** (bigger brick): SS1b, SS2b, SS3b, SS4b, SS5b
7. **Standard mixture + Lime** (small bricks): SL1s, SL2s, SL3s
8. **Standard mixture + Egg shells** (small bricks): SE1s, SE2s, SE3s
9. **Ricewater + Clay + Fine Sand** (small bricks): RCL1s, RCL2s

Each mixture has multiple specimens and some differentiate in size.

Some mixture we tested with small bricks(s), the other mixtures were tested with bigger bricks (b). Only the standard mixture was tested with small and big bricks. We tested two different sizes, since the strength of a brick wall is more influenced by the gaps between the bricks than by the bricks themselves. Bigger bricks reduce the amount of mortar and hopefully lead to stronger walls. It is also easier for unskilled workers to produce a wall with bigger bricks. [3]

<table>
<tr><td></td><td></td></tr>
<tr><td>Small brick (s)
Dimensions (cm): h=3, w=7, l=9,5</td><td>Big brick (b)
Dimensions (cm): h=4, w=8,5, l=17,5</td></tr>
</table>

Table of different brick dimensions.

1) Standard mixture Ss (Ss1, Ss2, Ss3, Ss4, Ss5)

Standard Mix	
clay	30%
fine sand	30%
coarse sand	40%
water (weight of t	10%

The standard mixture was given by Fred Veer. Clay gets mixed with fine and coarse sand to avoid shrinkage. The fine sand fills the gaps between the coarse sand and the clay particle fill the gaps between the fine and coarse sand. The clay functions as the binding material. Together with water the clay particles slide in between the sand. When drying they clay particles stay where they are and form the adobe brick.

2) Standard mixture + Wood chips SWs (SWs1, SWs2, SWs3)

Standard + Wood Chips	
clay	29,7%
fine sand	29,7%
coarse sand	39,7%
wood chips	1%
water (weight of t	10,00%

As the Standard mixture, this adobe recipe was given by Fred Veer. The wood chips make the brick lighter and therefore decrease the density of the brick. The chips could take some of the shear force or tension and increase the compressive strength. Too many would elongate the drying process and could cause mould on the surface of the brick, what would make them unusable.

3) Standard mixture + Ash (wooden) SAs (SAs1, SAs2, SAs3)

Standard + Ash (wooden)	
clay	27,27%
fine sand	27,27%
coarse sand	36,36%
wood ash	9,10%
water (weight of t	9,09%

After reading some articles about Roman concrete we found out that the used cement was based on Vulcanic ash (pozzolan) and lime (chalk). We added wooden ash to the standard mixture and hoped that the ash functions as some sort of binder. We decided to make one mixture only with ash, since it is easier available. [1][2]

4) Standard mixture + Ash + Lime (calcium hydroxide) (SALs1, SALs2, SALs3, SALs4, SALs5)

Standard + Ash +Lime	
clay	27,27%
fine sand	27,27%
coarse sand	36,36%
lime	4,55%
wood ash	4,55%
water (weight of t	9,09%

We tried to reproduce the Roman cement (lat. : cementitium) as described in Jackson et al (2017). Since our research showed that there is no Vulcanic ash near the camp we tried to subsidise it with wooden ash. The lime (chalk) could be produced on side from burning and calcination of lime stone. The problem with this mixture is that the tested bricks had one week to dry only. Lime usually needs at least 28 days to get its full strength. We assume that the moisture in this brick will be higher at the time of the testing. This could result in reduced compression strength and the bricks not to perform as good as expected. [1][2]

5) Standard mixture, bigger brick (Sb1, Sb2, Sb3, Sb4, Sb5)

Standard bigger format	
clay	30%
fine sand	30%
coarse sand	40%
water (weight of t	10%

Since the strength of a brick wall is defined through the mortar joints, we thought increasing the brick size could lead to a stronger wall. We assumed as well that a bigger brick can distribute inner tension or shear force better within itself and could therefore perform better in a compressive strength test. [3]

6) Standard mixture + Straw , bigger brick (SSb1, SSb2, SSb3, SSb4, SSb5)

Standard +Straw , bigger	
clay	29,7%
fine sand	29,7%
coarse sand	39,7%
straw	1%
water (weight of t	10,00%

The Straw mixture was given again by Fred Veer. The idea is that the straw functions as reinforcement and helps the brick to withstand tension and shear forces. It is important to mention that the right amount of straw is the key to success. Since too much straw makes the brick light and weak, also increases the risk of mould. Too little straw has no effect on the brick. The length of the added straw was around 3-5cm. Unfortunately, we did not have the time and space to look closer into different straw mixtures (longer or shorter fibres, straw content). We hope to gain more insight by comparing the results with other groups, who participated in the adobe workshop as well. [4]

7) Standard mixture + Lime (calcium hydroxide) (SLs1, SLs2, SLs4)

Standard + Lime	
clay	27,27%
fine sand	27,27%
coarse sand	36,36%
lime	9,10%
water (weight of t	9,09%

We wanted to use lime (calcium hydroxide) as a binding material. We think that it could be produced locally either from burning lime stone or egg shells. Like mortar we hoped the lime gives the mixture additional strength. We faced the same issue with lime as in the mixture "Standard mixture + Ash + Lime" since we tested the brick too early. Another problem we noticed ~~is~~ was the acidity of the lime. During the production we unfortunately did not wear gloves, what caused minor acid burns on our hands. We strongly recommend, like the package of the lime, to wear protective gloves and glasses.

8) Standard mixture + Egg shells (SEs1, SEs2, SEs3)

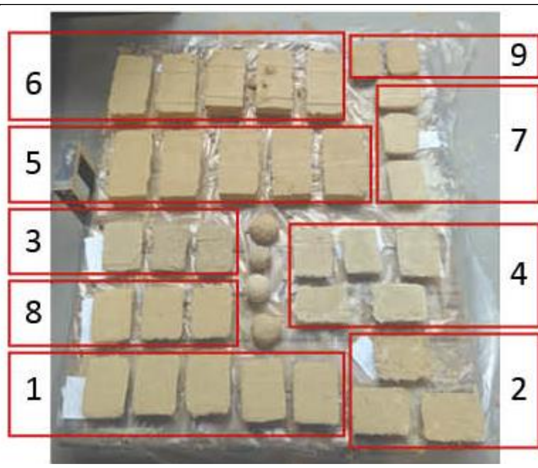
Standard + Egg shells	
clay	27,27%
fine sand	27,27%
coarse sand	36,36%
egg shells	9,10%
water (weight of t	9,09%

After Pirouz Nourian note, that egg white was used as a binder in historic construction, we decided to look further into this topic. We found a research paper that used Egg White as a natural admixture. Since we did not want to use food as a construction material we decided to try it with dried and grinded egg shells that still contained small amounts of egg white. We hoped that the small amount of egg white increased the strength. In addition, we thought that the grinded egg shell particles and the containing lime would have a positive influence on the strength too. [5]

9) **Ricewater + Clay + Fine Sand** (RCSs1, RCSs2)

Ricewater, Clay, Fine Sand	
clay	10%
fine sand	50%
rice water (weigh	50%

We wanted to use a waste product to produce a mixture. We thought that the water used to wash rice contains enough starch to influence the mixture. Since at this time there was no coarse sand available anymore, we decided to make a 50% clay and a 50% fine sand mixture. It would be necessary to check this mixture on shrinkage and appearing cracks when used for bigger bricks. Instead of water we used the starch containing water for this mixture. [6]



1) Standard mixture Ss (Ss1, Ss2, Ss3, Ss4, Ss5)
2) Standard mixture + Wood chips SWs (SWs1, SWs2, SWs3)
3) Standard mixture + Ash (wooden) SAs (SAs1, SAs2, SAs3)
4) Standard mixture + Ash + Lime (calcium hydroxide) (SALs1, SALs2, SALs3, SALs4, SALs5)
5) Standard mixture, bigger brick (Sb1, Sb2, Sb3, Sb4, Sb5)
6) Standard mixture + Straw , bigger brick (SSb1, SSb2, SSb3, SSb4, SSb5)
7) Standard mixture + Lime (calcium hydroxide) (SLs1, SLs2, SLs4)
8) Standard mixture + Egg shells (SEs1, SEs2, SEs3)
9) Ricewater + Clay + Fine Sand (RCSs1, RCSs2)

Table of all mixtures and produced bricks after drying one week.

2.6 Execution Plan

The first step was the production of the different adobe bricks on 25.09.2019 during the adobe making workshop. After the production of the bricks we measured them to find an average size of each group of specimens. After taking the dimensions we weighed the bricks. The volume and weight allow us to calculate the density.
Later the specimens were checked for cracks or other damages, it is worth to mention that we did not find any significant and mentionable damages or deformations.

To perform the test the specimens were placed in the compression strength testing machine. For the large bricks an additional load distribution (steel plate) was placed on top of the bricks. Before the test started, a label with the name of the specimen was placed before it and a picture was taken. After the test, the maximum compressive strength of each brick was noted by hand and a picture of the destroyed brick was taken.

The digital data from the compressive strength testing machine was collected and will be exported and graphed.

2.7 Measures Taken to Ensure Scientific Rigor

The measurements that were taken to ensure scientific rigor were mostly regarding the hand crafting adobe bricks. All bricks were made at the same day, temperature and location. The standard mixture was made with the same batch of clay, fine sand and coarse sand. The mixtures were made as accurate as possible but there is a possibility of light deviation since they were hand made and especially the water content could vary because of wetting the mould the bricks where shaped.

2.8 Research Instruments and Data Collection Techniques

- *Ruler:* used to measure the dimension of the specimens and the mould
- *Scale*: Used to weight the ingredients of the mixture and the bricks (before and after the drying process).
- Automatic digital compression testing machine (max. strength 100 kN): used to record data and perform the compressive strength test. Name of the machine?
- Camera: To take pictures before and after the adobe brick testing and to document the production of them.

3 Results

3.1 Given data and calculated Material Properties

The given data from the compression strength test and measurements leads to:

- Dimensions of specimens
- Compressive force before structural failure (Fmax)
- Deformation before structural failure (dL at Fmax)

This data will be used to calculate the following specimen or material properties [8]

- Area of the specimens (A=w*l)
- Fmax /Area
- E-Modulus (E=(F/A)/Strain)
- Strain = dL / L
- Max strain (assumption from literature)
- Safety factor (material specific) = Strain / Max strain
- Safety factor corrected Fmax = Fmax / Safety Factor

3.2 Results of testing for each group of specimens including estimation of ultimate strength, safe design strength per category

The maximum strain of adobe structure was researched in literature and was found to be between 10 and 20%. We decided to take the smallest strain of all tested specimens (Specimen S5b = 0.22) and divide it in half. That resulted in 0.11 which is equal to 11% and fits well into the results of the literature research. **Max strain = 11%.** This Value is applied on all specimens. [7]

1) **Standard mix** (Ss1, Ss2, Ss3, Ss4, Ss5)

   This group consists out of five specimens. We decided to ignore the best and worst values and take an average of the remaining values.

Code	Dimensional Properties (mm)			Fmax (N)	dL at Fmax (mm)	Area l*w (mm2)	Fmax/Area F/A (N/mm2)	E - Modulus Fmax / strain (MPa)	strain dl/l (-)	max strain (%)	safe fact. mat. strain / max strain	safe Fmax (N/mm2) Fmax / safe fact.
	l	w	h									
		Standard Mix										
S1s	95	70	30	9216	7.91	6650	1.39	5.26	0.26	0.11	2.40	0.58
S2s	95	70	30	21900	9.95	6650	3.29	9.93	0.33	0.11	3.02	1.09
S3s	95	70	30	17900	9.95	6650	2.69	8.12	0.33	0.11	3.02	0.89
S4s	95	70	30	20200	9.96	6650	3.04	9.15	0.33	0.11	3.02	1.01
S5s	95	70	30	16900	7.94	6650	2.54	9.60	0.26	0.11	2.41	1.06

The ultimate strength (Fmax) for this category varies from 1.39 to 3.29. To estimate the average ultimate strength we decided to eliminate the best and worst option and take the average of the three remaining values. This results in an estimation of ultimate strength:
(2,69+3,04+2,54)/3 = **2,75 N/mm² = Fmax.**
The Safety Factor is a result from dividing the strain with the maximum strain. Since a safety factor for each brick is not realistic we apply the same rule as before and eliminate the best and worst Safety Factors.
That results in: (3,02+3,02+3,02)/3= **3,02 = Safety factor**
By dividing the Fmax with the safety factor we get the safe design strength:
2,75 / 3,02 = **0,91 N/mm² = safe design strength**

Standard Mix (small)	
Fmax	2,75 [N/mm²]
Max strain	11%
Safety Factor	3,02
Safe design strength	0,91 [N/mm²]

2) **Standard mix + wood chips** (SWs1, SWs2, SWs3)

This group consists out of three specimens. Since ignoring the best and worst values is not an option, we decided to take the average of all specimens. We like to highlight that this group consists of too few specimens to give relevant data.

Code	Dimensional Properties (mm)			Fmax (N)	dL at Fmax (mm)	Area l*w (mm2)	Fmax/Area F/A (N/mm2)	E - Modulus Fmax / strain (MPa)	strain dl/l (-)	max strain (%)	safe fact. mat. strain / max strain	safe Fmax (N/mm2) Fmax / safe fact.
	l	w	h									
	Standard + Wood Chips											
SW1s	95	70	30	15900	7.97	6650	2.39	9.00	0.27	0.11	2.42	0.99
Sw2s	95	70	30	22700	7.96	6650	3.41	12.87	0.27	0.11	2.41	1.42
Sw3s	95	70	30	16700	7.98	6650	2.51	9.44	0.27	0.11	2.42	1.04

To estimate the average ultimate strength we decided take the average of the three values. This results in an estimation of ultimate strength: (2,39+3,41+2,51)/3 = **2,77 N/mm² = Fmax.**
The Safety Factor is a result from dividing the strain with the max. strain. For this calculation we take the average of all three values.
That results in: (2,42+2,41+2,42)/3= **2,42 = Safety factor**
By dividing the Fmax with the safety factor we get the safe design strength:
2,77 / 2,42 = **1,14 N/mm² = safe design strength**

Standard Mix + wood chips (small)	
Fmax	2,77 [N/mm²]
Max strain	11%
Safety Factor	2,42
Safe design strength	1,14 [N/mm²]

3) **Standard mix + Ash (wooden)** (SAs1, SAs2, SAs3)

This group consists out of three specimens. Since ignoring the best and worst values is not an option, we decided to take the average of all specimens. We want to mention that this group consists of too few specimens to give relevant data.

Code	Dimensional Properties (mm)			Fmax (N)	dL at Fmax (mm)	Area l*w (mm2)	Fmax/Area F/A (N/mm2)	E - Modulus Fmax / strain (MPa)	strain dl/l (-)	max strain (%)	safe fact. mat. strain / max strain	safe Fmax (N/mm2) Fmax / safe fact.
	l	w	h									
	Standard + Ash (wooden)											
SA1s	95	70	30	20000	7.92	6650	3.01	11.39	0.26	0.11	2.40	1.25
SA2s	95	70	30	12200	7.87	6650	1.83	6.99	0.26	0.11	2.38	0.77
SA3s	95	70	30	22500	7.94	6650	3.38	12.78	0.26	0.11	2.41	1.41

To estimate the average ultimate strength we decided take the average of the three values. This results in an estimation of ultimate strength: (3,01+1,83+3,38)/3 = **2,74 N/mm² = Fmax.**
The Safety Factor is a result from dividing the strain with the max. strain. For this calculation we take the average of all three values.
That results in: (2,40+2,38+2,41)/3= **2,40 = Safety factor**
By dividing the Fmax with the safety factor we get the safe design strength:
2,74 / 2,40 = **1,14 N/mm² = safe design strength**

Standard Mix + wood chips (small)	
Fmax	2,74 [N/mm²]
Max strain	11%
Safety Factor	2,40
Safe design strength	1,14 [N/mm²]

4) **Standard mixture + Ash + Lime (calcium hydroxide)** (SALs1, SALs2, SALs3, SALs4, SALs5)

This group consists out of five specimens. We decided to ignore the best and worst values and take an average of the remaining values.

Code	Dimensional Properties (mm)			Fmax (N)	dL at Fmax (mm)	Area l*w (mm2)	Fmax/Area F/A (N/mm2)	E - Modulus Fmax / strain (MPa)	strain dl/l (-)	max strain (%)	safe fact. mat. strain / max strain	safe Fmax (N/mm2) Fmax / safe fact.
	l	w	h									
	Standard + Ash +Lime											
SAL1s	95	70	30	9760	7.96	6650	1.47	5.53	0.27	0.11	2.41	0.61
SAL2s	95	70	30	8800	7.95	6650	1.32	4.99	0.27	0.11	2.41	0.55
SAL3s	95	70	30	14100	7.98	6650	2.12	7.97	0.27	0.11	2.42	0.88
SAL4s	95	70	30	20500	7.9	6650	3.08	11.71	0.26	0.11	2.39	1.29
SAL5s	95	70	30	14800	7.91	6650	2.23	8.44	0.26	0.11	2.40	0.93

The ultimate strength (Fmax) for this category varies from 1,32 to 3,08. To estimate the average ultimate strength we decided to eliminate the best and worst results and take the average of the three remaining values. This results in an estimation of ultimate strength:
(1,47+2,12+2,23)/3 = **1,94 N/mm² = Fmax.**
Since all individual safety factors are almost the same we decide to take an average.
That results in: (2,41+2,41+2,42+2,39+2,40)/5= **2,41 = Safety factor**
By dividing the Fmax with the safety factor we get the safe design strength:
1,94 / 2,41 = **0,80 N/mm² = safe design strength**

Standard mixture + Ash + Lime (calcium hydroxide)	
Fmax	1,94 [N/mm²]
Max strain	11%
Safety Factor	2,41
Safe design strength	0,80 [N/mm²]

5) **Standard mixture, bigger brick** (Sb1, Sb2, Sb3, Sb4, Sb5)

This group consists out of five specimens. We decided to ignore the best and worst values and take an average of the remaining values.

Code	Dimensional Properties (mm)			Fmax (N)	dL at Fmax (mm)	Area l*w (mm2)	Fmax/Area F/A (N/mm2)	E - Modulus Fmax / strain (MPa)	strain dl/l (-)	max strain (%)	safe fact. mat. strain / max strain	safe Fmax (N/mm2) Fmax / safe fact.
	l	w	h									
	Standard bigger format											
S1b	175	85	40	15000	9.94	14875	1.01	4.06	0.25	0.11	2.26	0.45
S2b	175	85	40	27400	9.77	14875	1.84	7.54	0.24	0.11	2.22	0.83
S3b	175	85	40	28000	7.87	14875	1.88	9.57	0.20	0.11	1.79	1.05
S4b	175	85	40	28700	9.92	14875	1.93	7.78	0.25	0.11	2.25	0.86
S5b	175	85	40	29400	8.76	14875	1.98	9.02	0.22	0.11	1.99	0.99

The ultimate strength (Fmax) for this category varies from 1.01 to 1,98. To estimate the average ultimate strength we decided to eliminate the best and worst option and take the average of the three remaining values. This results in an estimation of ultimate strength:
(1,84+1,88+1,93)/3 = **1,88 N/mm² = Fmax.**
The Safety Factor is a result from dividing the strain with the max. strain. Since a safety factor for each brick is not realistic we apply the same rule as before and eliminate the best and worst Safety factors.
That results in: (2,22 + 1,99 + 2,25)/3= **1,48 = Safety factor**
By dividing the Fmax with the safety factor we get the safe design strength:
1,88 / 1,48 = **0,80 N/mm² = safe design strength**

Standard mixture + Ash + Lime (calcium hydroxide)	
Fmax	1,88 [N/mm²]
Max strain	11%
Safety Factor	1,48
Safe design strength	1,27 [N/mm²]

6) **Standard mixture + straw bigger brick** (SSb1, SSb2, SSb3, SSb4, SSb5)

This group consists out of five specimens. We decided to ignore the best and worst values and take an average of the remaining values.

Code	Dimensional Properties (mm)			Fmax	dL at Fmax	Area	Fmax/Area	E - Modulus	strain	max strain	safe fact. mat.	safe Fmax (N/mm2)
	l	w	h	(N)	(mm)	l*w (mm2)	F/A (N/mm2)	Fmax / strain (MPa)	dl/l (-)	(%)	strain / max strain	Fmax / safe fact.
	Standard +Straw , bigger											
SS1b	175	85	40	35400	9.94	14875	2.38	9.58	0.25	0.11	2.26	1.05
SS2b	175	85	40	28000	9.97	14875	1.88	7.55	0.25	0.11	2.27	0.83
SS3b	175	85	40	29300	9.87	14875	1.97	7.98	0.25	0.11	2.24	0.88
SS4b	175	85	40	31600	9.92	14875	2.12	8.57	0.25	0.11	2.25	0.94
SS5b	175	85	40	44900	9.94	14875	3.02	12.15	0.25	0.11	2.26	1.34

The ultimate strength (Fmax) for this category varies from 1,01 to 1,98. To estimate the average ultimate strength we decided to eliminate the best and worst option and take the average of the three remaining values. This results in an estimation of ultimate strength: (2,38 + 1,97 + 2,12)/3 = **2,15 N/mm² = Fmax.**
Since all safety factors are almost the same we decided to take the average of all five specimens.
That results in: (2,26 + 2,27 + 2,24 + 2,25 + 2,26)/3= **2,25 = Safety factor**
By dividing the Fmax with the safety factor we get the safe design strength:
2,15 / 2,25 = **0,95 N/mm² = safe design strength**

Standard mixture + Ash + Lime (calcium hydroxide)	
Fmax	2,15 [N/mm²]
Max strain	11%
Safety Factor	2,25
Safe design strength	0,95 [N/mm²]

7) **Standard mixture + Lime (calcium hydroxide)** (SLs1, SLs2, SLs4)

This group consists out of three specimens. We decided to take the average of all specimens. We like to highlight that this group consists of too few specimens to give relevant data.

Code	Dimensional Properties (mm) l	w	h	Fmax (N)	dL at Fmax (mm)	Area l*w (mm2)	Fmax/Area F/A (N/mm2)	E - Modulus Fmax / strain (MPa)	strain dl/l (-)	max strain (%)	safe fact. mat. strain / max strain	safe Fmax (N/mm2) Fmax / safe fact.
		Standard + Lime										
SL1s	95	70	30	11800	9.93	6650	1.77	5.36	0.33	0.11	3.01	0.59
SL2s	95	70	30	17200	9.95	6650	2.59	7.80	0.33	0.11	3.02	0.86
SL3s	95	70	30	24800	9.94	6650	3.73	11.26	0.33	0.11	3.01	1.24

To estimate the average ultimate strength we decided take the average of the three values. This results in an estimation of ultimate strength:
(1,77 + 2,59 + 3,73)/3 = **2,69 N/mm² = Fmax.**
For the safety factor calculation we take the average of all three values.
That results in: (3,01 + 3,02 + 3,01)/3= **3,01 = Safety factor**
By dividing the Fmax with the safety factor we get the safe design strength:
2,69 / 3,01 = **0,89 N/mm² = safe design strength**
We assume that this mixture would perform better after a much longer drying time. Lime requires more time to reach its final strength.

Standard Mix + Lime (small)	
Fmax	2,69 [N/mm²]
Max strain	11%
Safety Factor	3,01
Safe design strength	0,89 [N/mm²]

8) **Standard mixture + Egg shells** (SEs1, SEs2, SEs3)

This group consists out of three specimens. We like to highlight that this group consists of too few specimens to give relevant data.

Code	Dimensional Properties (mm) l	w	h	Fmax (N)	dL at Fmax (mm)	Area l*w (mm2)	Fmax/Area F/A (N/mm2)	E - Modulus Fmax / strain (MPa)	strain dl/l (-)	max strain (%)	safe fact. mat. strain / max strain	safe Fmax (N/mm2) Fmax / safe fact.
		Standard + Egg shells										
SE1s	95	70	30	23700	9.92	6650	3.56	10.78	0.33	0.11	3.01	1.19
SE2s	95	70	30	27200	9.94	6650	4.09	12.34	0.33	0.11	3.01	1.36
SE3s	95	70	30	22400	8.67	6650	3.37	11.66	0.29	0.11	2.63	1.28

To estimate the average ultimate strength we decided take the average of the three values. This results in an estimation of ultimate strength:
(3,56 + 4,09 + 3,37)/3 = **3,67 [N/mm²] = Fmax.**
For the safety factor calculation we take the average of all three values.
That results in: (3,01 + 3,01 + 2,63)/3= **2,8 = Safety factor**
By dividing the Fmax with the safety factor we get the safe design strength:
3,67 / 2,8 = **1,31 [N/mm²] = safe design strength**
We assume that this mixture -performs better after a much longer drying time. Lime requires more time to reach its final strength.

Standard Mix + wood chips (small)	
Fmax	3,67 [N/mm²]
Max strain	11%
Safety Factor	2,8
Safe design strength	1,31 [N/mm²]

9) **Ricewater + Clay + Fine Sand** (RCSs1, RCSs2)

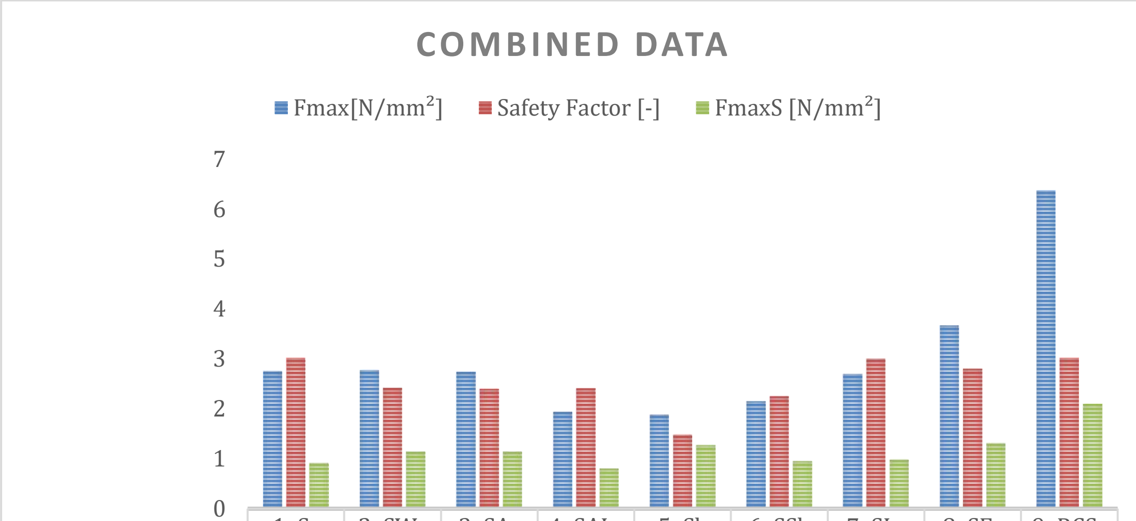
This group consists out of two specimens only. We decided to take the average of all specimens. We want to mention that this group consist of too few specimens to give relevant data.

Code	Dimensional Properties (mm)			Fmax (N)	dL at Fmax (mm)	Area l*w (mm2)	Fmax/Area F/A (N/mm2)	E - Modulus Fmax / strain (MPa)	strain dl/l (-)	max strain (%)	safe fact. mat. strain / max strain	safe Fmax (N/mm2) Fmax / safe fact.
	l	w	h									
	Ricewater, Clay´, Fine Sand											
RCS1s	95	70	30	54600	10	6650	8.21	24.73	0.33	0.11	3.02	2.72
RCS2s	95	70	30	30100	10	6650	4.53	13.62	0.33	0.11	3.02	1.50

To estimate the average ultimate strength we decided take the average of the two values. This results in an estimation of ultimate strength:
(8,21 + 4,53)/2 = **6,37 [N/mm²] = Fmax.**
For the safety factor calculation we take the average of all three values.
That results in: (3,02 + 3,02)/2= **3,02 = Safety factor**
By dividing the Fmax with the safety factor we get the safe design strength:
6,37/3,02 = **2,10 [N/mm²] = safe design strength**

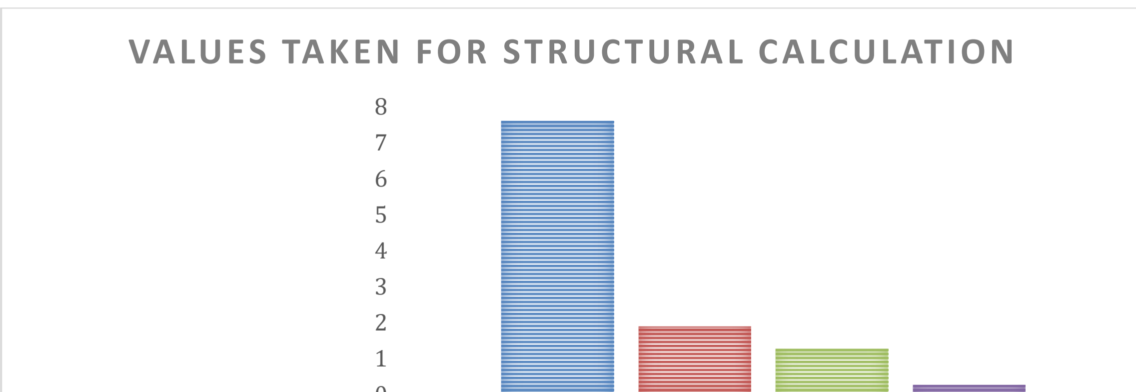
Standard Mix + wood chips (small)	
Fmax	6,37 [N/mm²]
Max strain	11%
Safety Factor	3,02
Safe design strength	2,10 [N/mm²]

3.3 Combined data



	1: Ss	2: SWs	3: SAs	4: SALs	5: Sb	6: SSb	7: SLs	8: SEs	9: RCSs
Fmax[N/mm²]	2,75	2,77	2,74	1,94	1,88	2,15	2,69	3,67	6,37
Safety Factor [-]	3,02	2,42	2,4	2,41	1,48	2,25	3,01	2,8	3,02
FmaxS [N/mm²]	0,91	1,14	1,14	0,8	1,27	0,95	0,98	1,31	2,1

As visible in the table above, most of the results for the safe compressive strength are approximately 1N/mm². Except the RCSs group that has around 2N/mm².



	Standard Mixture (Ss)
Youngs modulus[Mpa]	7,6
maximum compressive strenght [N/mm2]	1,88
maximum compressive strengh after safety factor [N/mm2]	1,27
maximum tensile strenght [N/mm2]	0,254

For the maximal tensile strength, we took 10% of the maximum compressive strength [9]. The chosen mixture is the standard mixture since it is the easiest to produce and requires no additional material.

As visible in the table above, most of the results for the safe compressive strength are approximately 1N/mm². Except the RCSs group that has around 2N/mm².

4 Conclusion / Reflection

The different mixtures showed different compressive strengths. After taking the safety factor into account those values are approximately 1N/mm², as found during the literature research. The strongest mixture was the mixture 9 RCSs. The strength of this mixture could be a result of the high clay content (50%) or the starch of the rice. The high clay content could cause tension and cracks during the drying process of larger bricks. Nevertheless, it is possible that the results of this small group are a population error. The effects of certain ingredients on the compressive strength of this mixture need further investigation and testing with bigger groups.
A surprise for us was the relatively high strength of the mixture 8 SEs. We suggest further investigation in this mixture to find out what caused the good performance under compression. We think it might be small egg shell pieces or traces of egg white that remained in the purposely unwashed egg shells.
To make the structure as safe as possible we decided to have a high safety factor. Therefore, we limited the max. strain to 11%. We did that to have as little deformation as possible in the structure considering that domes are sensible for deformation.

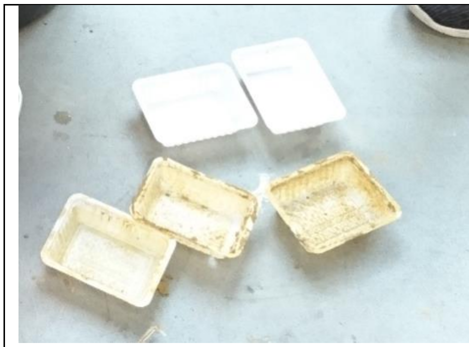
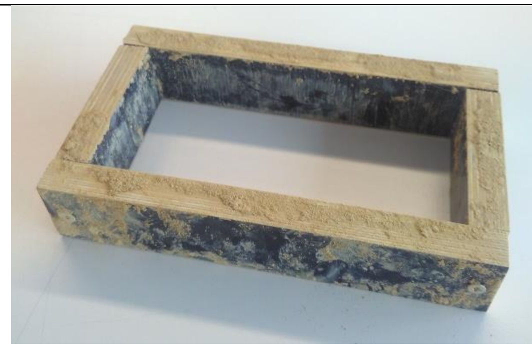
During the production we faced several problems due to the very soft moulds provided. The forms deformed and did not allow to produce adobe bricks with a consistent size. Also did the form not allow to compress dryer clay mixture since it just deformed when force was applied. To allow comparable results with other groups, we suggest providing the same form for each group. Larger batch numbers would be beneficial, we suggest at least ten specimens for each mixture. This would require a higher collaboration between the teams, but more valid results would be worth the extra work. To allow the use of additional binders like lime or gypsum, we recommend a longer drying phase.

Since we were using lime as a binding material as well we would have preferred a longer time between the production and the testing

5 Limitations of Study

5.1 Measurements Limitation

In this study, 34 specimens were manufactured and tested. Since the formwork for the small bricks was very thin, some bricks where deformed during the production. We can therefore not ensure the size of the bricks and only roughly estimate it. To produce big bricks we made our own formwork. This can be seen in the table below.

 Provided soft formwork that lead to deformation and unsimilar appearing bricks. We used it to handcraft the small bricks	 Selfmade formwork, based on traditional moulds to produce big bricks It produced clean edges and bricks with precise dimensions and smooth surfaces.
 Small uneven bricks from different mixture. The faces of the bricks are bulcky.	 Big even bricks with similar dimensions and clean surfaces

Formwork and its influence on the crafted adobe bricks.

For a follow-up study, every specimen should be produced with the same formwork. It can then be measured and evaluated to ensure every imperfection and therefore justify calculated results. We also strongly suggest a longer drying time to allow the investigation of additional binder such as calcium hydroxide.

The data we received from our brick testing was incomplete. We had to browse the table of 23 from 34 bricks manually to find the deformation at F max. We did this as accurate as possible but a possible error cannot be excluded.

5.2 Specimen Placement Error

During the experiment the specimens were manually placed in the automatic digital compression testing machine. This means that there could have been a method error when placing the brick not ideally in the middle. Therefore, this could have made a significant impact on the results and could have been a large factor for the inconsistencies in performance. This applies as well for the wooden board on which we placed the tested specimens. After several tests from different groups, the wooden board had a visible dent of several millimetres, that caused specimens to break. The test appeared to be almost a bending test until the tested brick

was pressured fully into the dent of the wooden board.
For a follow-up study, we would suggest drawing an outline on a massive steel base plate, in which the bricks should be placed.

5.3 Population Error

The sample used for this study consisted of 34 specimens from 9 different mixtures. Some mixtures had 2 or 3 specimens. The biggest group of mixtures had 5 different mixtures. This means that there is a possibility for a population error. The differences of the population can consist out of changes during manufacturing (mixture, handcrafted adobe, different water content, drying) But because we focused on the Young's modulus (which is a property of the material used in this research) the rest of the population became irrelevant.

5.4 Manufacturing Error

It is to worth to mention that a certain population error is wished since the production of the adobe bricks in Jordan will be by manual labour as well. Therefore there will be always small deviations from the mixture, temperature changes or not optimal drying condition, as well as human errors.

6 References

All Tables and picture are self-made, except if mentioned differently.

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