Adobe bricks as a structural material

A test report on the mechanical strength of adobe bricks.

Faculty of architecture and built environment
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Abstract

Building with earth is one of the earliest known form of construction in human history. It can be made with minimum number of tools, very low energy and soil, which is available everywhere. Thus by exploiting these benefits of the natural material 'adobe', a construction system is proposed in one of the most critical locations for human settlements - The Syrian refugee camp 'Zaatari' in Jordan. Bounded by the plight of minimal resources, the Zaatari camp gives us a platform for maximizing the use of the only available building material - sand and an investigation into extent of its use of mechanical properties. An experiment was performed to understand the behavior of the material which would aid in designing structures in the location. The report elaborates on the detailed process on this experiment and determining the mechanical properties which is evaluated for further use in architectural design. The experiment was a part of an academic curriculum for the faculty of architecture at TUDelft.

Key words: Adobe, earth architecture, compressive strength

Contents

1.Introduction

Adobe has been used as a building material for thousands of years in human history. Adobe comes from the Spanish word ''adobe'' referred to as sun dried brick, prepared by moulding the mud manually. It can be made with limited amount of resources like locally available soil and water. Its low environmental impact has proven to be promising over the vast variety of industrialised material in today's age. However, because of its versatile nature, there are no international codes for it as a building material, leaving the research to be dependant on private works of organisations or individuals.

This report is the result of an experiment on understanding adobe as a construction material, under the academic curriculum of the TU Delft Master programme of Building Technology. This experiment is a part of a architectural design studio - Earthy. The design proposal is for the Syrian refugees settled in Zaatari village in Jordan. Adobe has been chosen as the construction material for building shelters for the refugees, since sand is locally available in abundance at relatively low cost and it is the traditional building material of Syrians. The experiment aims to maximize the structural potential of the material by altering compositions and to provide a building solution in the disaster stricken area with limited resources.

The experiment aims to examine the mechanical properties of the various bricks made with adobe. The report elaborates on the brick making process by the students within the academic framework and university guidelines. These compression values generated after the tests will then be further used to design earth structures in Zaatari refugee camp.

1.1. Adobe Bricks as a historical building material

Adobe buildings are encountered in almost every region of the world and constitute a significant feature of the international cultural heritage. It's construction method has been developed particularly in hot-dry, subtropical and moderate climates (Gubasheva, 2017). The traces of its use dates to Mesopotamia in 10,000 BC, Turkistan 8000-6000 BC, Egypt 3200 BC, Assyria 4000 BC and Iran 500 BC (Gubasheva, 2017). Earth has been historically used as a building material not only for homes but for public buildings as well. Even in the 20th century around 30%-50% of the world's population lives (approximately 3 billion people) or works in earthen buildings. Approximately 50% of the population in developing countries, including most of rural population and 20% of urban population live in earth buildings (Houben & Guillaud, 1994).

Even after this major use of earth as a building material, there are still no globally accepted codes for this building material and its construction methods. Scientific data in this field is mainly by the research done by private institutes and universities worldwide. There is a huge variation in the scientific data and the numbers vary from place to place, thus, a detailed chemical and physical analysis of the material must be made before it is used locally.

Figure 1: World distribution of Earth architecture (Sensi, 2003)

1.2 Composition of adobe bricks

Adobe is a composite earth material, a little stronger than soil itself. The composition for adobe typically consists of sand, clay and silt (Wikipedia, 2018). They are not only different in size but also by their properties and role in brick manufacturing (Gubasheva, 2017). The sizes of these particles range from (Veer, 2018):

- Sand contains inert particles that range in size from 0.05 to 2.0 mm in diameter; it serves as a skeletal framework. Any sand is usable for making bricks, except beach sand which has a high salt content. However, extreme amount of sand can lead to weak and crumbly bricks (this can also be seen in the test results which are explained in later chapters).
- Silt contains polar particles having diameters of 0.002 to 0.05 mm. It has little cohesion when dry since its resistance to movement is less than that of sands. When exposed to various levels of humidity, silt swells, and shrinks changing in volume. (Gubasheva, 2017)
- Clay (also called coarse clay) contains fine polar particle less than 0.002 mm in diameter. Clay is the key component in adobe bricks. It makes the brick dense and increases the resistance to water erosion. However, it should be used in the right proportion otherwise it will cause the brick to shrink and crack in dry heat (Gubasheva, 2017).

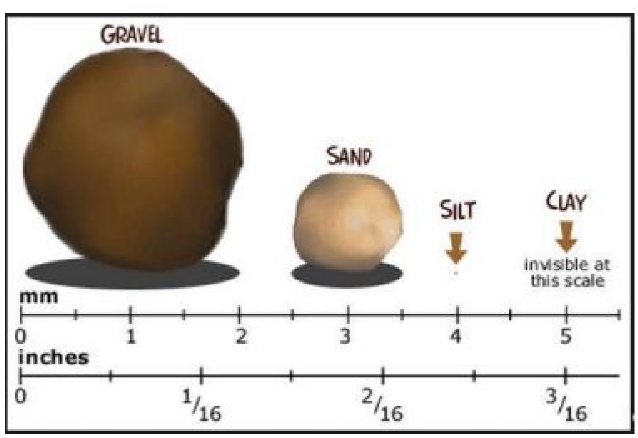


Figure 2: Sizes of soil particles (Gubasheva, 2017)

It is not recommended to use topsoil because of the significant amount of organic matter present that degrades, absorbs water and it highly compressible (Gubasheva, 2017). Apart from these three key ingredients, large aggregates like straw, dung, wooden chips, hair, hard fibres, ropes and cotton waste, chicken or barbed wire and dried sludge collected from waste-water plate can be used as binding materials to prevent cracking due to uneven shrinkage through the brick. In some cases stabilizers like portland cement, lime and bitumen are added in 5-10% of the total composition to increase durability and strength. However, adding such stabilizers is a more recent technique, adding significantly to the overall cost of the adobe construction. Thus, the use of these binders is avoided as much as possible.

Water is the main binding material of all the ingredients in adobe construction. Clay particles have a polar surface and water molecules are bound to these polar surfaces causing them to fix. The right amount of water is needed to shape them and a little less to fix them. Water is not bounded to pure sand particles chemically. Sand loses cohesion when the water dries out (Veer, 2018). Thus, a correct mixture of non-polar sand, clay, silt and water is needed to minimize shrinkage trains and optimize strength (Veer, 2018). This means that excess water that was used for shaping the brick needs to be removed by letting it evaporate from the surface of the object. Thus, the shape and size of the brick also matters to determine the strength of the brick and the larger aggregates like fibers aid in reducing shrinkage and even drying.

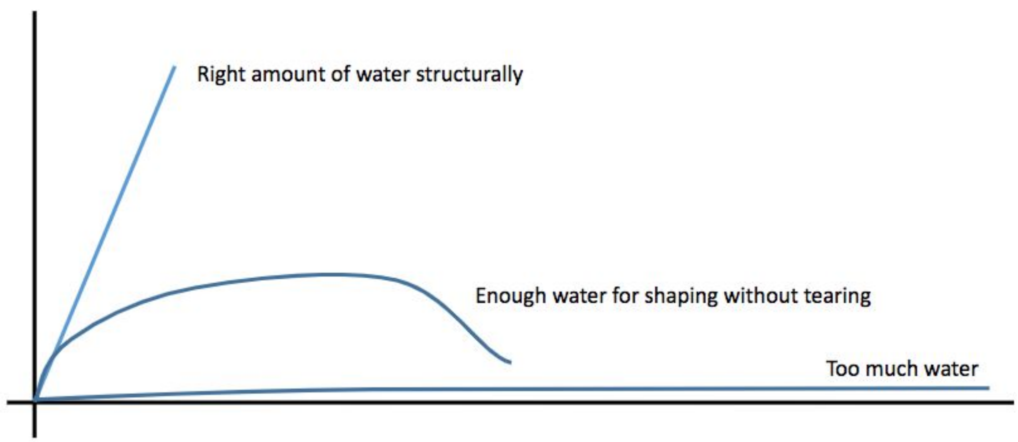


Figure 4: Force – displacement diagram (Veer, 2018)

2. Research methodology

The project requires developing a strong and durable mud brick for construction in a refugee camp by minimizing the amount of resources. Background research on adobe was done to get acquainted with the material and formulate a starting point for the research of the mechanical properties. In the experimental researches it was noted that the compressive strength of the adobe brick is dependent on the composition of soil i.e, the sand, silt, clay and water content, the size of the brick, the time of curing and the temperature at which it is cured (Sasui, et. al, 2017). However, only the first two criteria i.e, the composition and size of the brick has been taken into account for the purpose of this test. The limitations for curing time was bound by the schedule of academic framework. While the temperature control was limited by the open space available for curing in the campus, governed by natural temperature conditions in the city for a period of 7 days.

It should be noted that while the experiment is for the refugee camp situated in Zaatari, Jordan, the tests were conducted at the faculty of architecture at Technical University of Delft, The Netherlands. But since the materials were locally procured in Delft, the results of the test are an approximation of what could be expected in Jordan.

The research method was divided into the following steps:

1) Identifying earth as a building material in the refugee camp in Jordan.
2) Understanding the behaviour of mud as a building material by conducting a literature research. Understanding the various types of soil and its composition.
3) Formulating the appropriate benchmark recipe for adobe.
4) Procurement of the right tools and equipment for conducting the making of the bricks. Setting up a space for measuring, mixing, drying and storage of the bricks.
5) Following the guidelines for preparation of adobe brick specimens, under the rules of university.
6) Transportation of the specimens from the manufacturing tent to the material testing lab.
7) Setting up the compressive strength test in the material lab.
8) Assessment of the mechanical properties of the adobe bricks and analysis of the results.

The above steps were completed with a budget restriction for the course. Also, the use of power tools in the manufacturing process was used as an alternative to manual mixing because of university guidelines on hygiene and use of organic material within campus.

2.1 Research question

The main aim of the experiment is to investigate on what composition of the adobe brick will suit best for the context, given the resources that are locally available. The research question would be what are the suitable designed composition, compressive strength, young’s modulus for this project.

2.2 Theory and Equations

Compressive strength is the capacity of a material or structure to withstand loads tending to reduce size. Some materials fracture at their compressive strength limit; others deform irreversibly, so a given amount of deformation may be considered as the limit for compressive load (Wikipedia, 2018).

In this project, a displacement of 30mm (set in the compression machine) is considered the limit for compression load and the compressive strength is considered the strength when a fracture takes place and reaches the material failure, following the formula below:

$$\sigma = \frac{F}{A}$$

Where:
σ= Compressive strength (failure stress) [MPa]
F =Failure load [N]
A = Original specimen area [mm²]

The strain is defined as followed:

$$\varepsilon = \frac{\Delta H}{H}$$

Where:
Ɛ= Strain
△ H =Displacement [mm]
H = Original Height [mm]

Young's modulus is a measure of stiffness. It defines the relationship between stress and strain in a material in the linear elasticity regime of a uniaxial deformation (Wikipedia).

$$E = \frac{\sigma}{\varepsilon}$$

Where:
E= Young's modulus
σ= the uniaxial stress[MPa]
Ɛ= Strain

For adobes, Adobes under compression is non-linear and is characterized by intense plasticity and deformability (Illampas, et. al, 2011). But in their another study, a linear increase of stresses and strains was noted between 5% and 50% of the maximum load-bearing capacity(Illampas, et. al, 2013). In this case, the intervals for calculating the young's modulus were set near the 50% of the failure load.The positions of the failure load were marked in Appendix A

3. Manufacturing of adobe bricks

Adobe bricks are traditionally hand-made and sun-dried using natural materials. The energy consumption in making these bricks is negligible and the cost is relatively low. The process of making adobe may vary in different parts of the world, depending upon the availability of equipment, manpower and materials. The process described below is a modified method of making adobe, adopted to comply with the strict university rules of hygiene and usage of organic material within the campus. The method was formulated to mimic the traditional method of making adobe bricks. The following are the modifications made on the main process:

a) The use of power-tool (a concrete hand mixer) was used instead of the traditional shovel for making the mixture.
b) Plastic boxes were used as moulds instead of the traditional wooden/metal frames. The following is the method used to make the adobe bricks as an experiment to test the strength, under an academic framework.
c) The size of the bricks were dependant on the size of the plastic boxes, thus the original size of the bricks are different.
d) The local temperature of Delft is different from that of Zaatari, thus the drying of bricks at local temperatures could have slight effect on the mechanical properties.
e) The materials were locally procured in Delft for the experiment, the properties of these materials can be slightly different from that that is locally available in Zaatari.

3.1 Ingredients and equipment

Ingredients:

- Clay
- Silt
- Sand
- Straw
- Wood chips
- Potable Water

Equipment:

- Mixing tubs
- Buckets
- A powered, cement hand mixer
- Moulds
- A weighing scale
- A digital hygrometer

3.2 Process

Step 1: Making the base mixture with the right soil

The first step in adobe construction is identifying the right types of soil and knowing the properties of the local soil before using it in the mixture. The properties of the soil i.e., the clay content, is used to calibrate a correct recipe for the proportions of sand, silt and clay. There are no specific standards for this calibration and it is generally based on trial and error methods. The content of soil to produce quality adobe bricks has been mentioned by several authors. However, for the purpose of our test a pre-defined composition as mentioned below was taken as a benchmark to begin the test. Multiple variations of the composition were later tested in the laboratory to choose the best mixture.

To begin the test, a composition of:

- 30% clay
- 30% fine sand
- 40% coarse sand

was used as a base mixture (the quantities were adjusted in following samples so as to test the effect of different compositions). Water was added at the rate of 10% of the total weight of the dry mixture. The first batch composed of the following weight measurements:

- Clay - 3.75 kg
- Fine sand - 3.75 kg
- Coarse sand - 5 kg
  Total weight = 12.5 kg
- Water - 1.25 litre

First the clay, fine sand and coarse sand were measured using a weighing scale, as shown in figure 5 and the three types of soil were mixed in its dry state using a shovel. The different composition is mentioned in Table 1.

Figure 5: Measuring the quantity of ingredients using a weighing scale and mixing the three in a tub.

Step 2: Mixing water and preparing the mixture

The second step is to add water to the dry mixture. The measured quantity of water is added to create a sticky mixture. The mixture should not be too dry nor too liquidy. Potable water is used for making adobe bricks. Care must be taken that the water is not salty (especially sea-water), otherwise it will affect the overall strength of the brick in the long run. Figure 6 shows the mixing using a power-tool and its consistency. A traditional method of checking consistency is by conducting a drop test. The method consists of throwing a 4cm diameter ball of mix on the ground. The ball is thrown from a height of 1m or a person’s shoulder height. If the mixture is correct, the ball should not splatter nor crack and the mixture should stick together. If the mixture sticks together then it is ready for moulding process.

Figure 6: a) Weighing the water b) mixing the ingredients c) consistency of the mixture

After the base mixture of adobe was made, various combinations of mixtures were tried. It includes adding straw, wooden chips or extra sand/water. The initial mixture(M) consists of clay, fine sand, coarse sand, water, which were in the proportion of 3:3:4:1. Apart from it, the specimens were added different quantities of coarse sand (C), water (W), straw fibers (S), wood chips (WC) and paper shreds (P), obtaining thirteen mixtures. The details are in Table 1.

The proportions of the materials used in the specimens (by weight)						
Specimen number	**Name of the specimen**	**Clay**	**Fine sand**	**Coarse sand**	**Water**	**Additives (by volume)**
1	M(s)	*3*	3	4	1	/
2	M(l)	*3*	3	4	1	/
3	M(h)	*3*	3	4	1	/
4	M+0.1S(s)	*3*	3	4	1	10% Straw
5	M+0.1S(l)	*3*	3	4	1	10% Straw
6	M+0.1WC(s)	*3*	3	4	1	10% Wood chips
7	M+0.1WC(l)	*3*	3	4	1	10% Wood chips
8	M+0.3C(s)	*3*	3	7	1	/
9	M+0.1W(s)	*3*	3	4	1.2	/
10	M+0.15C+0.1W(l)	*3*	3	5.5	1.1	10% Paper shreds
11	M+0.3C+0.1P(s)	*3*	3	7	1	10% Paper shreds
12	C(Bottle blue)	/	/	1	/	/
13	C(Bottle yellow)	/	/	1	/	/

Note	The specimen numbers were named in the testing sequence in the machine. The additives were measured by volume comparing with the initial mixtures. (s),(l) and (h) represent small size, large size and handmade size respectively.

Table 1: Composition of adobe specimens.

Step 3: moulding process

Two sizes of plastic boxes were used as moulds for the adobe bricks. The sizes are as follows:

a) Small plastic mould - 75 x 120 x 65 mm
b) Big plastic mould - 105 x 158 x 58 mm

Generally the moulds are made of wooden frames which can vary in size as per the requirements but for the purpose of this experiment, plastic moulds were used. Two holes were made in the bottom of the mould, using a drilling machine. These holes aid in demounting the brick from the mould. After that the moulds were wetted with water or wrapped with clear plastic wrap so that the clay mixture does not stick to the walls of the mould. Finally the mixture was put in the mould till the top and pressed with hand. The mould was inverted, on a flat table covered with plastic, to get the brick out. Figure 7 shows the moulding process of the brick.

Figure 7: a) wetting the mould with two holes in its base. b) putting the mixture c) demounting the brick.

Step 4: Measuring the moisture content of the brick and drying

After the bricks are demounted, it is important to know the moisture content of the brick. This is done using a moisture meter. The bricks were laid in a table for drying. The drying period was 1 week. Since, each specimen was different in composition and size, it was important to label each with their specifications for reference during the compression test. A nomenclature was devised for easy identification of the composition with respect to the size. Figure 8 shows the arrangement of specimens for drying.

Figure 8: a) Moisture meter b) arrangement of specimens with labels.
(image (a) source: https://www.theairmovers.com/products/extech-mo210-moisture-meter-mo210-digital-pin-moisture-meter-with-bargraph-green)

3.3 Transportation

The bricks were made outside the model hall of the Faculty of Architecture at Technical University of Delft. Thus, they had to be transported to the material testing lab, which was situated 500m away from the modelling hall. A trolley cart was used to carefully transport the bricks. Care was taken to avoid jerks that could cause damage to the bricks during transportation.

4. Testing procedure

The testing procedure was taken at the Material Lab in the Faculty of of Mechanical, Maritime and Materials Engineering.

4.1 Measurement

The following explains the measurement process for the different specimens:

a) The volumes of the bottles were read from the product information in advance.
b) The lengths, widths and heights of the adobes, the diameters of the bottles were measured at two locations respectively, then the mean values were taken for stress calculation.
c) The relative humidities were measured using a digital hygrometer, which were inserted into the adobes when the adobes were taken out of the moulds.

4.2 Uniaxial Compression test

The adobes were trapezoidal prisms, the surfaces with smaller area were facing up when placing on the plate. A rectangular steel plate was placed above the adobes before applying load to make sure the load was transferred to the adobe evenly (see Figure 9).

Figure 9: A Steel plate placed above the specimen

As it is shown in Figure 10, the bottles were placed horizontally and the load was directly transferred from the machine platens to the bottles without the steel plate.

Figure 10: Specimen 12 before applying load.

In all tests, displacement and the loading force were measured from the machine's loading platens.

5.Results

5.1 Measurement

The dimension and relative humidity of the specimens						
Specimen number	**Name of the specimen**	**Length [mm]**	**Width [mm]**	**Height [mm]**	**Area [mm²]**	**Relative humidity[%]**
1	M(s)	75	120	65	9000	41.63
2	M(l)	105	157.5	57.5	16537.5	41.65
3	M(h)	79	142	44	11218	41.8
4	M+0.1S(s)	75	120	65	9000	42.25
5	M+0.1S(l)	105	157.5	57.5	16537.5	42.38
6	M+0.1WC(s)	75	120	65	9000	40.38
7	M+0.1WC(l)	105	157.5	57.5	16537.5	40.9
8	M+0.3C(s)	75	120	65	9000	42.23
9	M+0.1W(s)	75	120	65	9000	42.2
10	M+0.15C+0.1W(l)	105	157.5	57.5	16537.5	42.3
11	M+0.3C+0.1P(s)	75	120	65	9000	41.88
Specimen number	**Name of the specimen**	**Length [mm]**	**Volume [mm³]**	**Height [mm]**	**Area [mm²]**	**Relative humidity[%]**
12	C(Bottle blue)	190	500000	58.7	8517.9	/
13	C(Bottle yellow)	180	400000	58.2	6872.9	/
Note	For bottles: The height is the mean diameters of bottle body. Area= Volume/ Height					

Table 2: Dimension and relative humidity of the specimens

5.2 Compression test

Since the fractures in the adobes took place earlier than the time the deformations reached 30mm, the compressive strength (failure stress) was considered the strength when a fracture took place and reached the material failure. For the two bottles, the deformation at the failure loads of

the bottles were the loads where the strain achieved 50%, because by the time the bottles reached the machine maximum displacement setting of 30mm, the strain already exceeded 50%.
When calculating the failure stress, it was assumed that the adobe area remained the same before crushing, the pressure area of the bottles is the equal to their volume divided by their height (Area= Volume/ Height).
The points of the failure load and the intervals for calculating the young's modulus were marked in the Stress-strain diagrams of each specimens in Appendix A
The test results are in the table 3.

Compression test result						
Specimen number	**Name of the specimen**	**Failure load (Fmax) [N]**	**Displacement at failure load [mm]**	**Area [mm²]**	**failure stress(σ) [MPa]**	**Young's modulus (E) [MPa]**
1	M(s)	3390.286	2.414	9000.0	0.377	17.590
2	M(l)	18668.520	7.215	16537.5	1.129	17.590
3	M(h)	16890.930	5.002	11218.0	1.506	22.699
4	M+0.1S(s)	8821.698	8.677	9000.0	0.980	10.311
5	M+0.1S(l)	20394.240	9.495	16537.5	1.233	8.852
6	M+0.1WC(s)	6846.074	11.306	9000.0	0.761	4.710
7	M+0.1WC(l)	33128.870	20.181	16537.5	2.003	10.388
8	M+0.3C(s)	4682.800	2.270	9000.0	0.520	21.790
9	M+0.1W(s)	2871.022	2.870	9000.0	0.319	13.046
10	M+0.15C+0.1W(l)	16603.520	1.840	16537.5	1.004	9.710
11	M+0.3C+0.1P(s)	80271.200	29.995	9000.0	8.919	77.774
12	C(Bottle blue)	41334.930	29.321	8517.9	4.853	26.260
13	C(Bottle yellow)	59251.410	29.071	6872.9	8.621	11.117

Table 3: Compression test results.

5.3 Failure behaviour

Adobe bricks

All the adobe specimens had similar failure behaviors. At the beginning of the loading, a few vertical cracks appeared from the top. When the load increased, more cracks propagated parallely to the load direction and they extended to the bottom. At the same time, the side surfaces fell off in pieces and the vertical deformation kept growing. After reaching the peak load, both the vertical and horizontal deformation developed faster. In the end, although the side surfaces had significant damages, the central remained integer (see Figure 11).

Figure 11: a) Specimen 1 during applying load b) Specimen 1 after loading

Because of the composition differences, slight distinctions did exist. Compared with the specimen consisted of only initial mixture, Specimen ‘M+0.1S(s)’ and ‘M+0.1S(s)’, which were with extra straws, as well as Specimen ‘M+0.3C+0.1P(s)’ which with extra paper shreds and Specimen ’ M+0.3C(s)’ which contained extra coarse sand, had less pieces fell off on the side surfaces. In addition, no rupture of the straw or paper shred was observed in the test.

Bottles

In the test of the first bottle (Specimen 12), the pressure area was compressed obviously while the rest of the surface remained the same. The second bottle (Specimen 13) was compressed more evenly on the top surface but still have dents at two sides where the edges of the load platens were. (see Figure 12)

In the end, both bottles didn't reach the failure load due to the machine maximum displacement setting of 30mm.

Figure 12: a) Specimen 12 after loading b) Specimen 13 after loading

6.Discussion

6.1 Compressive strength and Young's Modulus

The compressive strength of adobe specimens (which involved mixing soil with water and straws) from different manufacturers in Cyrus was found to be in the range 0.2 to 1.6 MPa when the maximum allowable deformation was set at 1.5%, whereas values between 0.5 and 3.2 MPa were obtained when failure was assumed at 5% deformation (Illampas, et. al, 2011) In another study, the compressive strength ranges from 0.66 to 1.98 MPa, which took adobes from the existing houses in Aveiro district, Portugal (Silveira, et. al, 2012). A mean compressive strength of 1.5 MPa and the biggest difference among 6 specimens of 0.3 MPa were measured from the adobe cubes at the age of 1 months (Blondet and Vargas,1978).

In this project, the biggest difference among the adobes specimens was 8.542 and the compressive strength ranged from 0.319 MPa to 8.919 MPa. Except compressive strength of the specimen 'M+0.1WC(l)' with wood chips and the specimen 'M+0.3C+0.1P(s)' with extra coarse sand and paper shreds, others were corresponding to the literature study.

Young's modulus in the test were from 4.710 to 77.774 MPa, only the specimen 'M+0.3C+0.1P(s)' reached the numerical range of the literatures, which were old adobe bricks from 51 MPa to 340 MPa (Silveira, et. al, 2012) and adobes with various percentages of soil, coarse sand, water and straw fibers from 98 MPa to 211 MPa (Gubasheva, 2017).

In general, the compressive strengths were acceptable based on the literatures and the young's modulus were too low, which means the stiffness is too low considering serviceability. All the adobes in this test were hand-made by several persons, causing the quality differences (such as density, surface smoothness) among the specimens. The divergence in the composition, the making process(such as curing time, production environment), the testing procedure (such as loading speed, specimen shape) could be responsible for the differences among the literatures and this test.

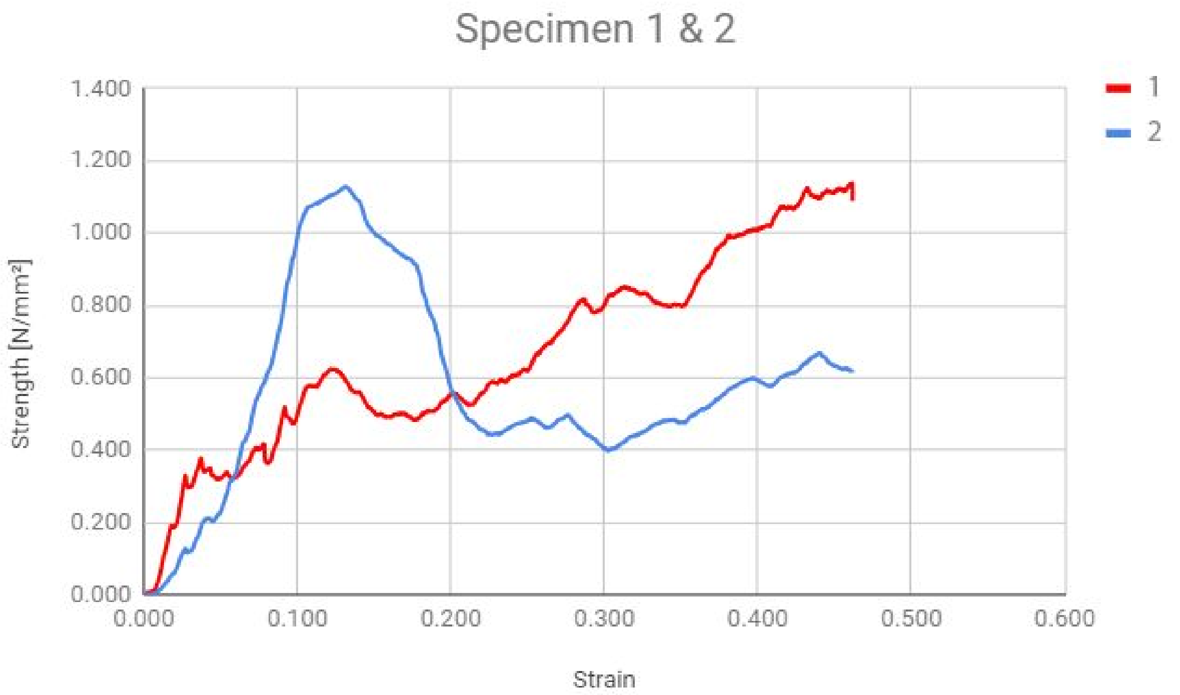
Specimen 13 'Bottle Yellow' had a uneven body. Therefore here only considered Specimen 12 'Bottle blue' for the comparison with the adobes. Except the Specimen 11 'M+0.3C+0.1P(s)', the compressive strength of the bottle was almost 2.5 to 13 times larger than those in adobes and its young's modulus was only 3.56 MPa lower than one adobe (Specimen 3).

6.2 Influencing factors of Failure stress

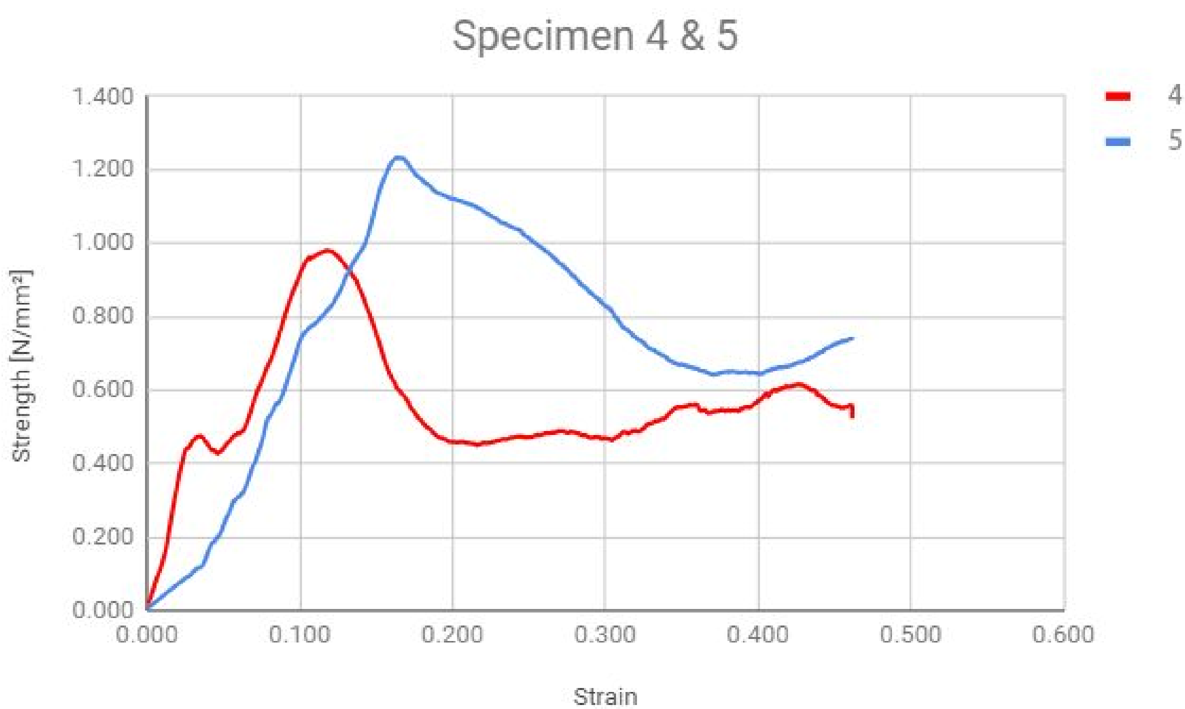
- **Size**

  Specimen 1 and 2, Specimen 4 and 5, Specimen 6 and 7 shared the same composition respectively, but Specimen 1, 4, 6 were in a smaller size (75 x 120 x 65 mm) and Specimen 2, 5, 7 were in a bigger size(105 x 158 x 58 mm).

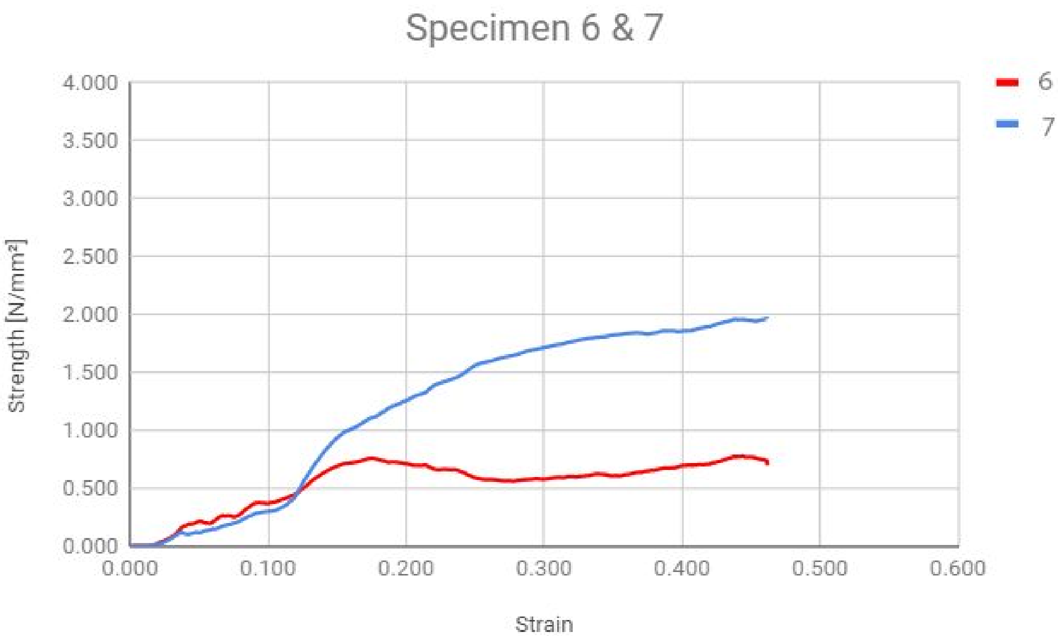
In these three graphs, no relationship between small and big adobes was found.



Graph 1: Strength/ Strain graph - Specimen 1 and 2



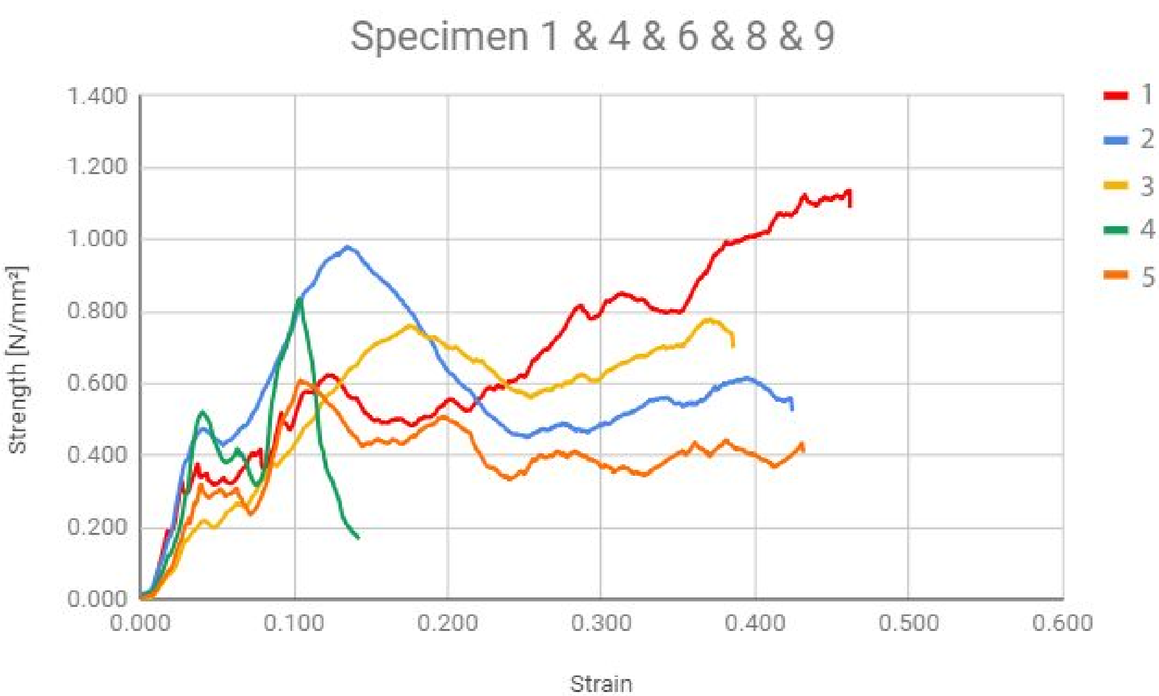
Graph 2: Strength/ Strain graph - Specimen 4 and 5



Graph 3: Strength/ Strain graph - Specimen 6 and 7

- **Composition**

  Specimen 1, 4, 6, 8, 9, 11 had the same size but different compositions. The strength of specimen 11 was so high compared with other specimens that it affect the visually in the graph. So here Specimen 11 was not in the consideration. According to Graph 4, the compositions of the adobes had significant influence on the strength-strain curve.



Graph 4: Strength/ Strain graph - Specimen 1, 4, 6, 8 and 9

6.3 Safety factor and Design strengths

Buildings commonly use a factor of safety of 2.0 for each structural member (Wikipedia).
The adobes in the project would be all man-made, quality difference would exists between adobe bricks or bottles or the integration with mortar. Also, the mechanical properties may suffer deterioration which cause the performance worse than the new built buildings. Moreover, due to serviceability, the deformation should not be visible or unrecoverable (avoiding fractures and large strains). The safety factor in this project was set to be 2.

For the design strength of adobe,eliminating the Specimen 11, M+0.3C+0.1P(s), whose strength was highly above others, the average compressive strength of adobes was 0.98 MPa and the mean value of young's modulus was 13.69 MPa. Specimen 2, whose strength of 1.129 MPa and young's modulus 17.590 MPa, was regarded having the best material composition that led to good mechanical properties among all the adobe specimens (excluding Specimen 3, which was made without a mold therefore no size control). In conclusion, the design strength was decided to be 1.129 MPa and the composition of the materials were clay, fine sand, coarse sand and water in the proportion of 3:3:4:1 (by weight).
For earth bottle design, the compressive strength(4.853 MPa) and the young's modulus(26.260 MPa) of specimen 12 (the weaker one) were chosen to be use in this project.

7.Limitation

The experiment was conducted under an academic framework which had to comply with the university guidelines. Thus certain limitations governed the results of the experiment. Also the availability of resources like materials and budget constrained our extent of research. Since the curriculum demanded a timely submission of the output, the experiment had to be modified to suit the time frame, thus time was limited during the scope of study. The setup was made in the university in Delft, thus these results are an approximation of what can be expected in Jordan. As the materials for experiment ie. sand, clay and silt were not procured from Jordan, the results might vary from its actual values. Also the bricks were dried in the natural temperature and not a controlled environment, thus the relative humidity and temperature during the drying process could affect the strength of the bricks.
The first stage of experiment consisted of manufacturing the bricks, certain power tools were used to make the mixture, as a compulsion under the university guidelines. Also plastic boxes were used as moulds, these plastic boxes were not of the same size as that of an original adobe brick. The output of these plastics moulds were uneven surfaces, whose impact could be seen during the load tests. Also, the shrinkage in the bricks have not been taken into consideration for this load test. The different compositions for the mixture were limited and many possible potential combinations remain unexplored. Finally certain level of measurement error is accounted for in the results during dimensioning and measuring which may have slight effects on the value.

8.Conclusions

The project aims at developing earth as a building material and minimizing other resources in the construction of refugee camp. To have a better understand toward earth as a building material and set up criterions for design, the making process was conducted in the Faculty of Architecture and the Built Environment and uniaxial compression test were executed in the Faculty of of Mechanical, Maritime and Materials Engineering.

In the making process, thirteen specimens were made by a group of 10 students, the variants including the size, the composition, adobe or bottle, with or without mold. After 7 days of curing in the tent without turning them over, the specimens were transported in plastic bags carrying by students and in a trolly for the test.

From the laboratory test, all specimens undertook considerable cracking and deformation. They shared the similar behavior of failure, first the cracks appeared and the side surfaces began to fall off. Then the cracks propagated into fractures and more pieces fell off from the four sides. Finally the side surfaces had significant damages, the central remained integer. However, straws, paper shreds and extra coarse sand helped reducing the peeling. On the other hand, the bottles were compressed but did not receive damage when the displacement achieved 30mm and the machine stopped loading.

The stress-strain development of these specimens displayed significant variations. The failure load was set at the moment when the first fracture generated. The compressive strength and the young's modulus of the adobes were from 0.319 MPa to 8.919 MPa and from 4.710 to 77.774 MPa respectively. The compressive strength and the young's modulus of the bottles were 4.853 MPa and 26.260 MPa respectively. From the test it was obvious that the composition had influences on the mechanical performance but the relationships were not clear. It could not be concluded that the size affects the strength from this test.

Considering quality difference among specimens, environmental deterioration and serviceability, a safety factor of 2 was defined. For adobes, a design strength of 1.129 MPa, a young's modulus of 17.590 MPa and the composition of the materials were clay, fine sand, coarse sand and water in the proportion of 3:3:4:1 (by weight) were chosen for the project. For bottles, a design strength of 4.853 MPa, a young's modulus of 26.260 MPa was set.

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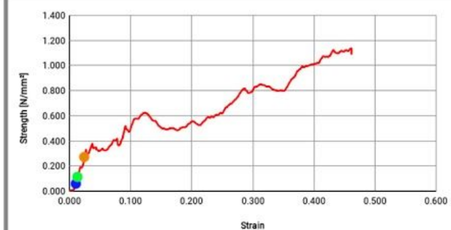
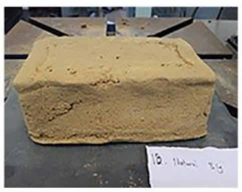
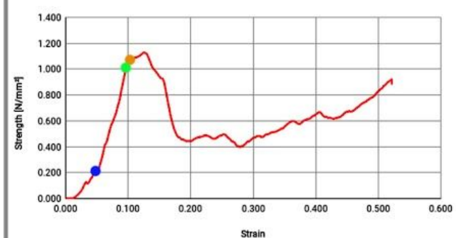
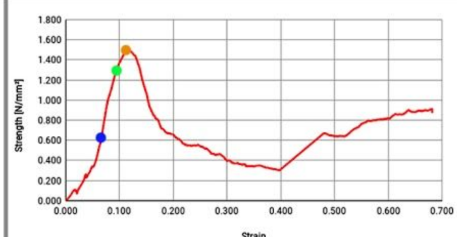
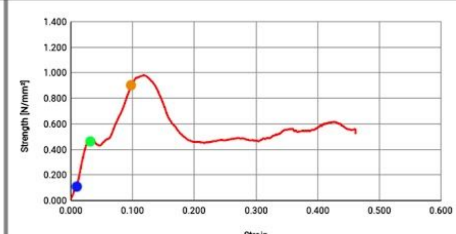
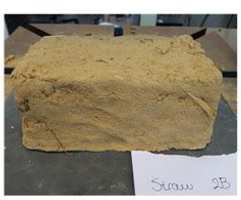
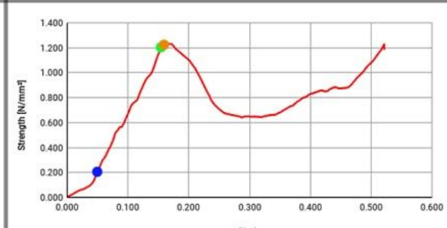
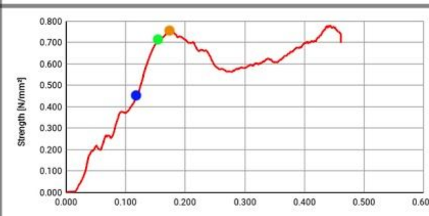
Appendix A

Specimen Number	Specimen before test	Specimen after test	Stress/Strain Curve ● Lower limit ● Upper limit ● F(max)
1			
2			
3			
4			
5			
6			

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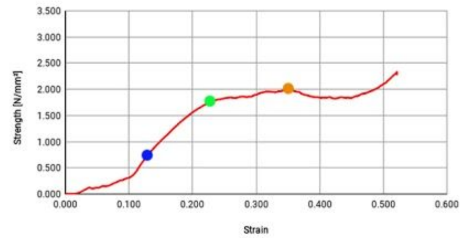
● Lower limit
● Upper limit
● F(max)</th></tr>
<tr><td>7</td><td></td><td></td><td>
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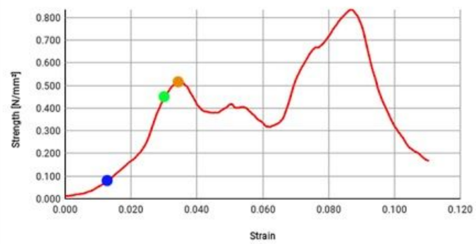
<tr><td>8</td><td></td><td></td><td>
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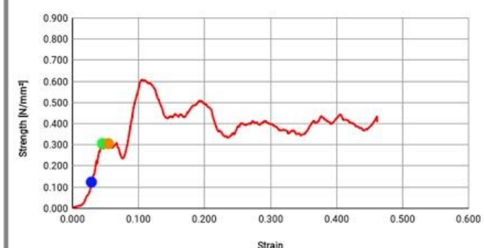
<tr><td>9</td><td></td><td></td><td>
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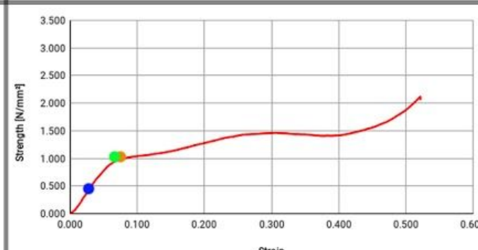
<tr><td>10</td><td></td><td></td><td>
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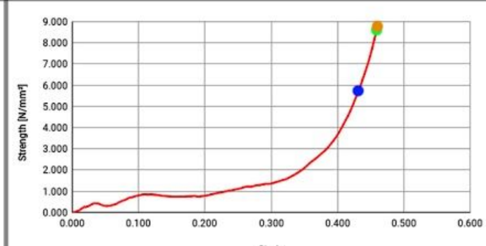
<tr><td>11</td><td></td><td></td><td>
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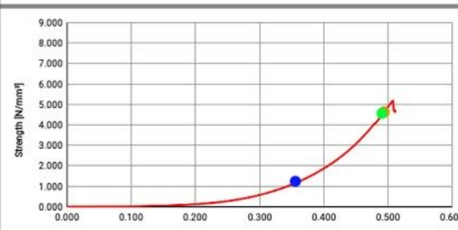
<tr><td>12</td><td></td><td></td><td>
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</table>

Specimen Number	Specimen before test	Specimen after test	Stress/Strain Graph ● Lower limit ● Upper limit ● F(max)
13