Czech Technical University in Prague

Faculty of Civil Engineering

Department of Concrete and Masonry Structures

Bachelor Thesis

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Statutory Declaration

I declare that I have developed and written the Bachelor Thesis completely by myself, and have not used sources or means without declaration in the text. Any thoughts from others or quotations are clearly marked. All the materials I have used for the Bachelor thesis are listed in the references.

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Adobe bricks as a building material

Abstract

Adobe – is one of the oldest building material, made from earth and some organic materials. The availability, simplicity of manufacture, and minimal effort for long-term maintenance of Adobe bricks made this material popular throughout the world. With its high thermal capacity, adobe construction is perfectly adaptable for use in the cold as well as in hot and dry areas. However, nowadays, this oldest building material started to attract more attention because of its minimal ecological impact to the environment.

The Bachelor thesis focuses in the description of Adobe brick from various perspectives, and plenty of reasons why the Adobe bricks should be admitted it as a Building Material and their manufacture restarted are presented.

Keywords: *Adobe, Adobe brick, construction material, eco-efficient brick, earthen construction.*

Content

1.Introduction

Nowadays the use of nonindustrial materials has been rediscovered because of the environmental problem caused by the extreme use of the industrial materials. The concept of nonindustrial building materials means local materials manufactured using a simple, fast process with low embodied energy using raw materials from the site or nearby. Unburned Adobe brick one of the notable example of nonindustrial material, which might be the clue to better life on Earth.

Adobe means mudbrick in Spanish, but in some English-speaking regions it refers to any kind of earth construction, as most adobe buildings are similar in appearance to Cob and Rammed earth buildings [4]. It is one of the earliest building material, which was used throughout the world.

Adobe bricks are most often made into units weighing less than 100 pounds and small enough that they can quickly air dry individually without cracking and be subsequently assembled, with the application of adobe mud, to bond the individual bricks into a structure [4]. They are made from clay reach soil, natural fibers, sand and water. We can refer them to “unburned masonry”, which means – baked (dried) in the sun. Adobe has been used in construction since ancient times due to cultural, climatic and economic reasons.

Adobe house is made of adobe bricks or monolithic adobe walls. Adobe walls are load bearing, i.e. they carry their own weight into the foundation rather than by another structure [4]. The molded into any shape and size depending upon requirements. The cost of the Adobe brick is much cheaper in comparison with other building materials and it makes Adobe more available.

2.History

Earth is one of the earliest construction material. It has been extensively used for the construction of walls and buildings for 1000 years around the world (some recorded cases of the use of earth blocks date back to Mesopotamia around 10.000 BC), particularly in all hot-dry, subtropical and moderate climates and those countries where there is not much vegetation, so there is a lack of wood [1].

For many centuries, hand-molded unburnt earthen bricks (adobes) have been used for load-bearing masonry structures. Adobe is a very simple earth building technique, and maybe this is the reason why most ancient structures were made of it. The word ''adobe'' come from the Arab "*attob"*, which means sun-dried brick.

Adobe construction was prolific in the ancient world, and archaeologists discovered surviving examples in many various places. Earth brick buildings were found in Turkistan (dating back to about 8000-6000 BC), in Assyria (from about 4000 BC) and monumental earth structures can be observed still today in upper Egypt (from about 3200 BC). The historical city of Shibam in the south of Yemen is completely built by adobe (about the fifteenth century) [1]. In India, the oldest earthen building is Tabo Monastery, in Spiti valley - Himachal Pradesh. It was also built with adobe and has withstood Himalayan winters since 996 AD [3]. But the largest structure ever made from adobe is the "Arg-e-Bam" built by the Achaemenid Empire, which is dating at least 500B.C. (Iran) [4].

Earth was used as the building material in all ancient cultures, not only for homes but for religious buildings as well. Figure 1.1 shows vaults in the Temple of Ramses II at Gourna, Egypt, built from mud bricks 3200 years ago. Figure 1.2 shows the citadel of Bam in Iran, parts of which are ca. 2500 years old; 1.3 shows a fortified city in the Draa valley in Morocco, which is around 250 years old [2].

Many centuries ago, in dry climatic zones where wood is scarce, construction techniques were developed in which buildings were covered with mud brick vaults or domes without formwork or support during construction. Figure 1.4 shows the bazaar quarter of Srdjan in Persia, which is covered by such domes and vaults. In China, twenty million people live in underground houses or caves that were dug in the silty soil [2].

1.1 Storage rooms, temple of Ramses II, Egypt [2].

1.2 Fortified city, Draa valley, Morocco [23].

1.3 Citadel of Bam, Iran, before earthquake of Dec. 2003 [24]

1.4. Bazaar, Sirdjan, Iran [2].

During the seventeenth and eighteenth centuries, earth block technique was commonly used in England and Scandinavia, and European immigrants brought it to the United States, where a large number of earth houses were built between the eighteenth and nineteenth centuries [1]. The oldest example of mud brick walls in northern Europe, found in the Heuneburg Fort near Lake Constance, Germany (1.5) dates back to the 6th century BC [2].

1.5. *Reconstruction of mud-brick wall, Heuneburg, Germany, 6th century BC [2]*

3.Adobe buildings around the world

The use of Adobe is very common in all hot-dry, subtropical and moderate climate zones, where is a lack of wood and vegetation, such as the Middle East, Africa, Latin America, Caribbean, Indian subcontinent, part of Asia, Pacific and Southern Europe, as shown in Fig-1.6.

1.6 World distribution of earth architecture (source: De Sensi 2003)

Around 30% to 50% of the world's population (about 3 billion people) lives or works in earthen buildings (Rael 2009). Approximately 50% of population in developing countries, including a majority of the rural population and at least 20% of the urban population, live in earthen dwellings [8]. For example, in Peru, according to the 2007 Census, almost 40% of houses are made of earth (that's two million houses inhabited by around nine million people) [8]. In India, according to the 2001 Census, 30% of all buildings are made from earth (this includes 73 million houses inhabited by almost 305 million people).

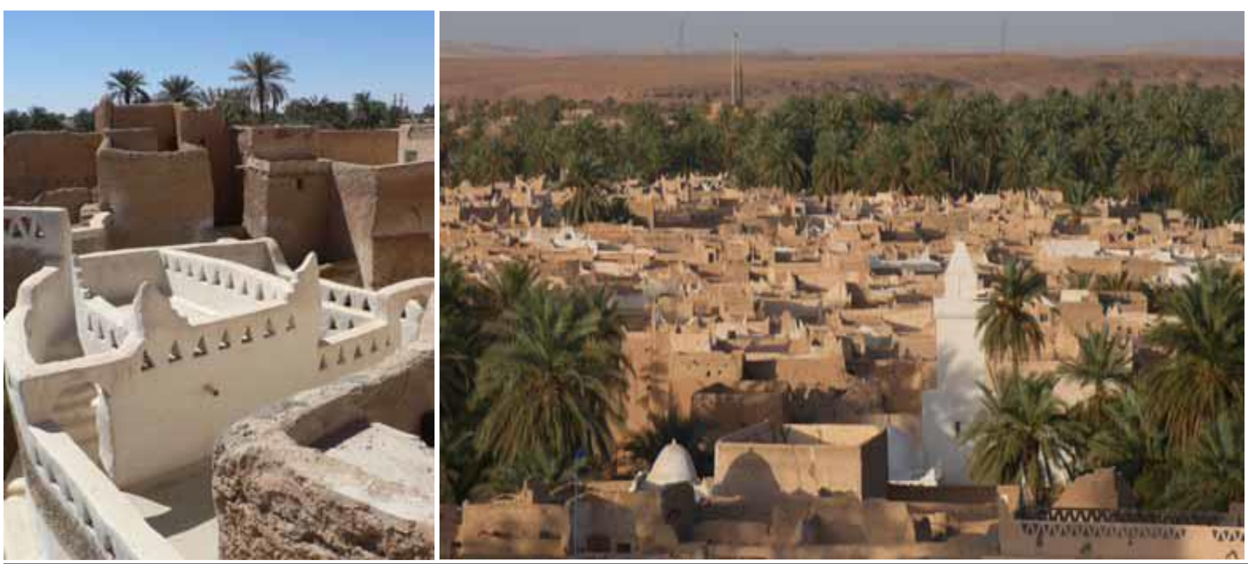
Adobe construction is mostly used in countryside areas. Houses are typically one-story high, with wall heights of around 3.0 m and thicknesses ranging from 250 mm to 850 mm. In mountainous areas with steep hillsides such as the Andes (Peru), houses can be up to three stories high. In parts of the Middle East and Asia, earthen houses are often built one on top of the other, so that the roof of one house is used as the bottom floor of the house above. Adobe houses are found in the urban areas of most developing countries, like Iran, Bolivia, Ethiopia, Uzbekistan, etc.

Below are examples of the most popular Adobe buildings from different continents.

<u>Africa</u><u>*. Mali. Old Towns of Djenne*.</u> For over a millennium they used earth in the form of cylindrical bricks shaped by hand and, since the early 20th century, in the form of adobe. The method of construction was transmitted from father to son.

1.7. Great Mosque of Djenne [6].

<u>The Arab States</u><u>*. Libya. Old Town of Ghadames*</u>*.* Ghadames, known as 'the pearl of the Sahara Desert', stands in an oasis. The overall urban fabric was built of toub (adobe), which made exceptional comfort in the arid climate. (Period of construction is I century BC- XX century AD)



1.8.-1.9. General view of the old town Ghadames [6].

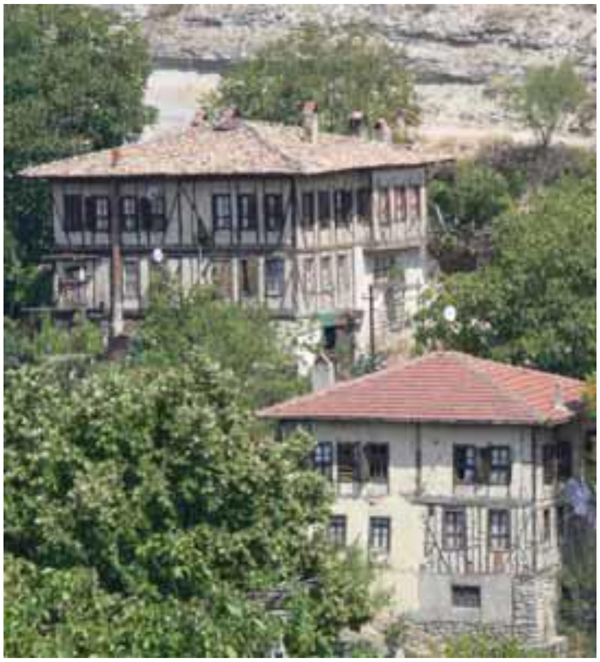
***Central Asia**. Iran. Bam city.* The Fortress of Bam is made entirely from unbaked adobe masonry with mud mortar. These bricks have several types according to the time of manufacture. For example, large bricks of various sizes used for enclosure walls and vertical structures, and small and fine bricks (about 25x25x5cm) used for the construction of vaults and domes.

2.1. Stable, Citadel of Bam, before its destruction in 2003 [6].

***Central Asia**. Uzbekistan. Itchan Kala.* It is the inner town (protected by 10 meters high brick walls), which was the last resting place of caravans before crossing the desert to Iran. Many buildings were made of adobe. Itchan Kala is a coherent and well-preserved example of the Muslim architecture of Central Asia. (‘*kala’* from Uzbek means ‘town’)

2.2. Walls of Itchan Kala [6].

***Europe**. Turkey. City of Safranbolu.* About half of the oldest houses in the city are wood-frame filled with adobe or brick. This technique is particularly well suited to the city with high seismicity, as Safranbolu.



2.3 - 2.4 Wood-framed buildings in Safranbolu [6]

***North America.** USA. Pueblo de Taos.* It is an adobe settlement, situated in the valley of a small tributary of the Rio Grande. This settlement consists of dwellings and ceremonial buildings, which represent the culture of the Pueblo Indians of Arizona and New Mexico.

2.5 Adobe constructions in Pueblo de Taos [6].

Latin America. *Mexico. San Miguel de Allende.* This city was built in the year 1542. Adobe is a widely-used building material in both civil and religious architecture of San Miguel. Also, the use of pink limestone in the building is very popular in this place.

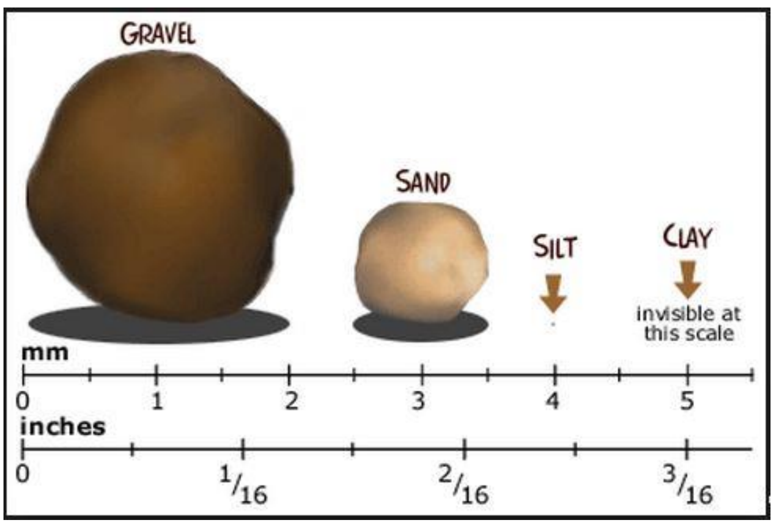
2.6. Spanish colonial adobe buildings in the historic center of San Miguel de Allende [6].

South America. *Bolivia. City of Potosi.* City founded by the Portuguese in 1680 on the Rio de la Plata, and still has around 160,000 inhabitants. One or two level houses were constructed of Adobe bricks bonded with earth mortar. But most of the public and religious buildings were built of stone.

2.7. View to the City of Potosi [6].

4.Composition of Adobe brick

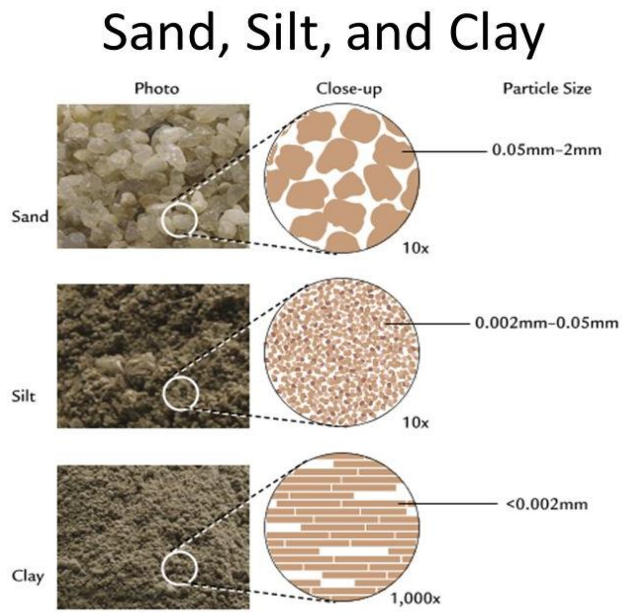
The actual composition of adobe brick depends on the raw materials, which are varying in quality by the amount of gravel, sand, silt, clay and organic material (straw). Sand, gravel, silt and clay are soil particles. They are different not only by their size but also by their properties and role in adobe brick manufacture (Figures 2.8 - 2.9). The soil used for making Adobe bricks refers to an in situ sandy loam subsoil. Also, it is not recommended to use the topsoil, because of the significant amount of organic material present, that biodegrades, absorbs water and is highly compressible. The components of adobe brick, in fact, can be considered as analogous to those of concrete: the inert aggregate fraction is represented by granular soils (sand and gravel), and the binder fraction is represented by cohesive soils (silt and clay).



2.8 Sizes of soil particles [25]

<u>*Clay*</u> is the key component in adobe bricks. It is a fine grained (approximately 0.002mm) soil material, which consists mainly of microscopic clay mineral particles. Clay makes bricks dense, acts as a binder, and increases the resistance to water erosion. Clay holds bricks together as cement in a concrete block. Nevertheless, too much clay is unfavorable to brick composition, since it may cause them to shrink and crack in the dry heat. The origin of clay minerals is found in the interaction of water and rocks (silicate minerals). It can be written as “water + rock = clay.” This shows that the clay is hydrous - and more so than the minerals in most rocks. There are several various kinds of clay and all of them are usable for making adobe brick.

Silt is made up of particles the size of which range between nearly 0.002 and 0.06 mm. It has little cohesion when dry since its resistance to movement is lower than that of sands. Nevertheless, silt displays cohesion when wet. When it is exposed to various levels of humidity, silt swells, and shrinks, changing clearly in volume. Gravel, sand, and the less amount of silt, are characterized by their stability in the presence of water. However, when they dry, they have some cohesion. Thus, they cannot be used on their own as fundamental materials of a building.



2.9 Differences between soil particles [26].

Gravel and *sand* serve as a sort of skeletal frame. The size of gravel is between 2 and 20 mm, and sand's much smaller between 0.06 and 2 mm. Sand helps to limit the quantity of cracking due to both the shrinkage that appear during the initial drying as well as the expansion that results from relative amounts of moisture at other times. However, extreme amounts of sand can lead to weak, crumbly bricks. Any sand is usable in making bricks, except beach sand, which contains a huge amount of salt. Because salt is hygroscopic material and it has negative consequences for building materials.

Straw serves as a stabilizing material, to make admixture less sticky and more workable during the actual mixing process and, most importantly, it helps to improve the tensile strength of adobe bricks. In other words, straw binds a brick together and allows it to shrink without cracking. Straw (ancient Egyptian *dhi,* Arabic *tibn),* and sometimes chaff, has always been the universally preferred type of temper used throughout the Near East; whenever this is not a readily available commodity, alternatives may include chopped grasses or weeds, tree bark, and potsherds [5]. Scientists appropriately distinguish between different classes of vegetal temper according to their origin and coarse-sieving cereals. By highlighting their commonly assigned various uses: (1) "fragmented light straw" is the type of vegetal fiber most commonly used in adobe bricks; (2) "medium-coarse winnowed straw" is more common in mud plaster or it may use as fuel; and (3) "chaff," which results from a later step during cereal processing, can be applied to bricks or wall plaster. These fibers serve several major functions: (1) they significantly decrease the bulk density of the brick, lightening its weight and reducing its thermal conductivity; (2) they accelerate drying by improving outward drainage of moisture to the surface of the brick; (3) they prevent cracking upon drying by distributing tension throughout the bulk of the brick; and (4) most importantly, fibers increase the tensile strength of the adobe brick. In addition, since fibrous adobes have less the thermal conductivity, they provide heat (energy, fuel) savings in buildings [10]. In most Asian countries instead of straw, people are using rice husk, bamboo, bagasse, hemp and sometimes animal hair. It is known that, in practice, straw fibers addition is suggested to be about 5-10 g/m3; however, as clay content increases, this proportion can be increased, even if some authors recommend that the fiber content should be restricted about 0.5 percent be weight [1].

3.1 Straw fibers [27]

4.1. Adobe mineralogy: Characterization of Adobes from around the world

In 1990, Richard Coffman [14] and another three scientists published the research *"Adobe mineralogy: Characterization of Adobes from around the world."* They did a mineralogical survey of adobes from several historical and modern earthen structures in various parts of the world. Adobe samples were collected from eight places. These include historic adobe from Egypt (one sample - 3500 years old), China (two samples - 600 years old and 1400 years old) and, El Salvador (two samples – 1365 years old), New Mexico (100 years old) and Israel (two samples – 3800 years old), and modern adobe from New Mexico and USA (southern California). Preliminary results of the research showed that variation in clay mineralogy and grain size distribution plays important roles in the success or failure of chemical consolidation. Whole rock and clay mineralogy of adobes were gotten by X-ray diffraction (XDR) analyses. And here are interesting facts and analytical results of this research:

- XRD analyses of bulk and clay mineralogy's showed that the most adobes are composed of quartz, feldspar, clay, and sometimes calcite. The prevalence of quartz and feldspar in adobe is expected since they are the most common materials on the earth's surface. And the calcite, which acts as cement, is a common mineral in arid or semi-arid environments.
- Only in China samples occurred chlorite, which proves that different source place leads to the different composition.
- In grain-size distribution for the adobe, the majority of the material is silt-sized.
- Adobe contains varying quantities of soluble materials ranging from only a few percent up to 27% by weight.
- The most resistant adobe to disaggregation is 1365-year-old two samples from El Salvador. These two samples were in water 24 hours without disaggregating, even when mildly agitated. The reason for this phenomenon might be the volcanic eruption in 625 A.D. in El Salvador. Because, as we know, the heat makes adobe brick much more resistant to disaggregation than unbaked adobe.
- Samples of Adobe which disaggregated quickly in water, contain more clay than the resistant adobe samples, or the same amount of clay and a higher sand content, and/or a reduced amount of organic materials.

In conclusion of this research, the most noticeable differences between the various Adobe samples are the mineralogical proportions, the type, and amount of clays present and the grain-size distribution.

5. Technology of manufacture of Adobe brick

As was written before, Adobe bricks are different with their simple manufacture. The shape of the block does not have any restrictions, and it can be various. For example, in the Central Asia people are used to mold the bricks in the shape 20 x 40 x 20 cm, however in Latin America in size 43 x 43 x 11 cm. The time for producing earth brick is during spring or autumn because the sun is not much strong and so there is not a rapid drying process that can produce cracks. If the manufacture of Adobe bricks is necessary during summer or winter, so it is good to adopt some precautions: in the first case, samples should be covered with wet straw to avoid excessive drying; while in the second case, they have to be covered with dry sand, to allow good seasoning of earth blocks also in humid and cold weather.

Place of the process basically depends on sediment, water, and open space. Taken together, these three constraints provide a strategic challenge for cost-efficient manufacture of bricks on a large scale.

5.1. Steps of Adobe brick manufacture

1st step – Finding a suitable soil

Before making any type of Adobe brick, we must find the best quality of clay rich soil. This type of soil usually on the top or side of natural hill. The soil in a dry water bed or low lying areas that can be flooded should be avoided, because it is full of rocks and gravel and does not contain any clay.

To be sure about clay content in the soil, the test with the glass jar with water is the best, simple solution. We need to fill a glass jar about 2/3 of soil and add a water until the jar is full. Shake it for about 2 minutes, then let it sit overnight. In the end, the sand should be settled on the bottom with the clay on the top. The amount of sand must be higher, approximately 75-80 percent. So, 20-25 percent of clay in the soil and this is ideal for making Adobe brick.

2nd *step – Sieving process*

After finding the right soil for manufacture Adobe brick, it must be sieved for filtering and screening. The holes of the sieve should have the diameter the same as the minimum diameter of the gravel particle size (i.e. 2mm), because there is no need of large gravel in the soil for Adobe brick production.

3.2. Sieving process. [14]

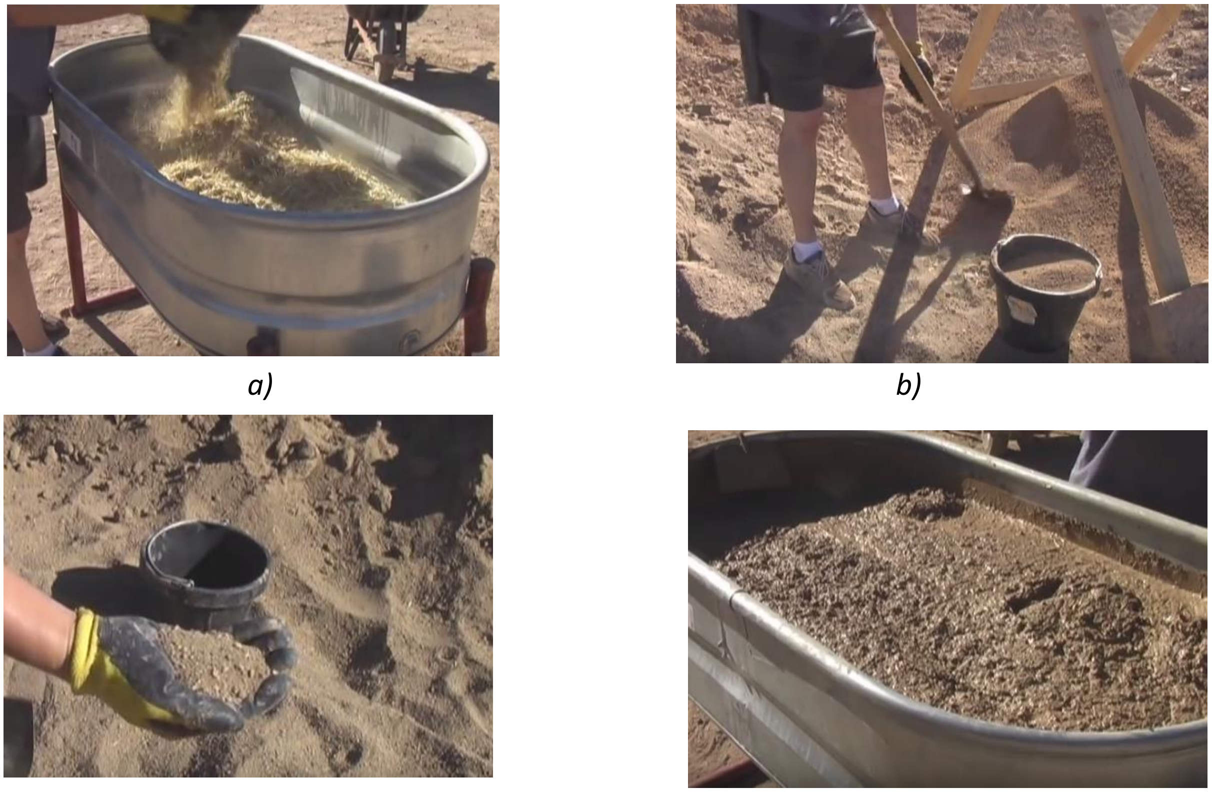
3rd step – Mixing process

The materials which are used to manufacture the Adobe brick are clay rich soil, coarse sand, straw, and water. These materials are mixed together with specified proportion. For the mixing station can be used feed trough (*Fig. 3.3.a*), also be needed garden hoe (*Fig. 3.3.b*) to make the process easy and 3-gallon stiff rubber buckets (*Fig. 3.3.c*) to have exact volumes of ingredients.

Firstly, four buckets of water should be added to the station with two buckets of chopped straw *(Fig. 3.4.a)*. After mixing them little a bit, adding there seven buckets of clay rich soil *(Fig. 3.4.b)* and seven buckets of coarse (grain size) sand *(Fig. 3.4.c)*. And, never try to make a mixture more workable by just adding more water since this reduces the strength and durability of the mixture. Finally, prepared Adobe mix *(Fig. 3.4.d)* can be used for the next step.

a) b) c)

3.3. a) feed tough; b) garden hoe; c) stiff rubber buckets; [14]



a) *b)* *c)* *d)*

3.4. a) the addition of chopped straw; b) clay rich soil; c) coarse sand; d) Adobe mixture; [14]

<u>*4th step – Molding process*</u>

There are 50 wooden forms *(Figure 3.5.a)* in 6 bricks each with a dimension of 10 x 14 x 3.5'' (approximately 25.4 x 35.6 x 7.6 cm). Molding is a very simple process, just transferring Adobe mixture to the molds by wheelbarrow, then with a long screed *(Figure 3.5.b)* or by hand distributing the mixture. Some people prefer to wet the molds before the process, but it is not necessary. During the hot or windy weather, after the molding, addition of the little water is helpful to keep the clay content relatively high and avoid rapid drying.

<u>*5th step – Drying process*</u>

If you had a wet mix, it is better to pull the forms off *(Figure 3.6.a)* next day after the molding process. Next step is carefully standing bricks up on end *(Figure 3.6.b)* because this will help them to dry out. It might be done after one day or two days maximum, depending on the weather. Once bricks dried in the field for a week, you can put them on wooden pallets *(Figure 3.6.c)* for another two-three week by keeping little space between each sample.

In the end, they are ready to be used to construction.

a)

b)

3.5. a) wooden forms; b) distribution of the Adobe mixture into the molds; [14]

a)

b)

c)

3.6. a) pulling the forms off; b) standing bricks up on end; c) bricks on the wooden pallet; [14]

6. Material properties of Adobe brick

Adobe brick - is available, cheap, reusable, eco-efficient material, which does not need a big amount of energy for its production and application. Besides, Adobe walls are load bearing, i.e. they carry their weight into the foundation rather than by another structure and these massive walls provide very high thermal, acoustic and fire resistant properties. The Adobe brick does not get mechanical strength as high as concrete or burnt brick. However, the Adobe is strong enough, ductile and resistant against earthquake.

With these properties, today, the forgotten Adobe construction techniques are gaining popularity and importance in developed countries.

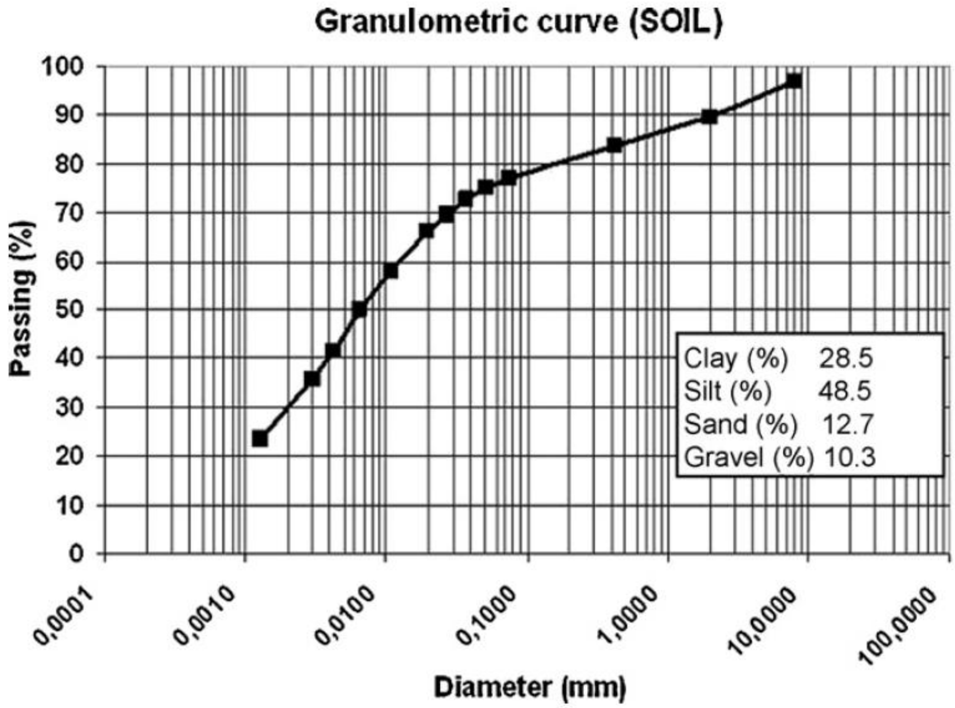
6.1. Mechanical properties of Adobe brick. Experimental Program.

Mechanical properties of adobe brick directly related to the composition of raw materials. This topic was fully described in the Enrico Quagliarini's research – "The influence of natural stabilizers and natural fibers on the mechanical properties of ancient Roman adobe bricks." The study tries to characterize the mechanical properties (i.e., workability, compressive strength and Young modulus) of adobe bricks, assessing how different weight percentage of natural stabilizers (sand) and natural fibers (straw). Also, the ancient Roman adobe brick represents non-industrial ecological material, which can be used nowadays. Results will lay the basis to characterize the mechanical behavior of adobe walls better.

6.1.1. Materials for experimental program

The materials used in this study for adobe brick production were soil as the main matrix; coarse sand as a stabilizer; straw as fibrous materials and water as a lubricant.

The soil used in this investigation refers to an on sandy loam subsoil, which directly came from the 2m of depth ground, because as was written before, the topsoil is unsuitable due mainly to the significant amount of organic material present that biodegrades, absorbs water, and is highly compressible. Its geotechnical characterization is "Lean Clay with Sand," which is classified as CL



3.7. Grain composition of the on situ clayey soil [12]

according to Unified Soil Classification System. Grain size distribution of the materials was determined according to ASTM D422, and in *Figure 3.7* is shown the soil texture.

Particularly, its clay content is a bit greater than 25%. But the latest research [11] showed that the requirement for the suitable soil for building material has to contain less than 20% clay minerals, so it seems appropriate adding a granular soil, such as coarse sand. The coarse sand used is a “Well-graded sand with gravel”, which is classified as SW according to Unified Soil Classification System (ASTM D2487) [12]. It was composed of sand 61.8% (by weight) and gravel. The last raw component in this experiment, straw, has been cut in a fiber of about 0.05m and with a length included in a range between 0.02 and 0.08 m. Straw can decrease hygrometric shrinkage because of both its traction strength and, above all, of its gradually water-releasing capability.

6.1.2. Sample production for experimental program

The production of earth bricks started during spring. Departing from an only-soil composition (E), it was added different quantities in the volume of coarse sand (C) and straw fibers (S), obtaining ten mixtures [12]. A lightly variable volume of water was added to reach a sufficient workability of the mixture: when coarse sand and fiber content was increased, water content also increased a little *(Table 1)* [12]. In any case, workability water contents are about the same level. Therefore, comparison of these samples is appropriate.

Name of mixtures	Soil volume	Coarse sand volume	Straw volume	Water volume	Workability
E	1	0	0	0.17	Scarce
E + 0.5C + 0.25S	1	0.50	0.25	0.28	Scarce
E + 0.5C + 0.5S	1	0.50	0.50	0.27	Scarce
E + 0.5C + 0.75S	1	0.50	0.75	0.27	Good
E + C + 0.25S	1	1	0.25	0.31	Good
E + C + 0.5S	1	1	0.50	0.33	Good
E + C + 0.75S	1	1	0.75	0.35	Scarce
E + 1.5C + 0.25S	1	1.50	0.25	0.34	Very good
E + 1.5C + 0.5S	1	1.50	0.50	0.34	Very good
E + 1.5C + 0.75S	1	1.50	0.75	0.38	Very good

Table 1. Proportions of soil, coarse sand and straw fibers used in mixtures and mixtures workability during bricks production [12]

All the mixtures have been produced by a mixing machine, except E-mixture (mixed manually). Then, they have been manually compacted in a wooden frame that was first wet with water and scattered inside with sand, as to reduce water absorption by wood. The moistened soil was compacted in separate layers, and the surplus has been removed. Frame for adobe brick had a removable bottom that allowed an easy removal of the sample by simply catching mold by handle and shaking it. In addition, the table 1 also shows mixtures workability noticed during brick production.

In the end, 20 bricks have been produced (2 bricks for each kind of mixture). Each sample's dimensions were equal to 0.31 x 0.46 x 0.13 m3.

Seasoning place had an average temperature of 26 ◦C and an average relative humidity of 47% [12]. After 2 months seasoning time, all samples were particularly dry, with the average water content about 2.45%. Then each brick had been cut in four parts, thus, the mean size of each adobe block was 0.15×0.23×0.13m3 *(Figure 3.8).*

The test results were found on the average of the compressive strengths and Young modulus of eight specimens for each mixture [12]. Before testing all the samples, dimensions and imperfections have been signed up to process, better analyses and understand experimental data.

3.8. Sun dried Adobe bricks for the experiment [12]

6.1.3. Testing procedure

Compression tests were set to allow uniform distribution of loads on samples. So, a layer of sand has been put on the lower steel plate to lay samples flat, compensating for irregularity of the sample bottom face; a transparent film has been put on the sand *(Figure 4.1)* [12]. The sand layer also allows a decrease of friction at the plate–sample interface. After sample brick placing, it has been put a transparent film over it and a sand layer again. The upper transparent film role was to avoid sand to fill cracks during the test procedure *(Figure 4.1*) [12]. All adobe bricks were tested along the direction they had been pressed into the wooden mold. Eight blocks for each mixture had been tested, in total - 80 samples.

The apparatus used for compression tests on blocks was a "Galdabini" universal model of first class with an 1% error with an end scale of 400 kN [12]. It has two transducers: for pressure and for bottom plate displacement (vertical displacement). The applied displacement rate was set to $0.03 N/mm^2 s$).

6.1.4. Test results

In the *Table 3*, are reported the average of the maximum compressive crushing stress (compressive strength, $\sigma_{max\ mean}$), of the Young modulus (E_{mean}), of the strain corresponding to the maximum compressive stress ($\varepsilon_{\sigma max}$), of the internal water content ($\omega_{int\ mean}$) for each typology of samples. Also, there presents the lowest and the highest peak value of the compressive stress (σ_{max}) for each type of sample. A nominal ultimate strain ε_C appears in *Table 3*, too. This is necessary to compare the strain performance of the various samples. The actual ultimate value of the recorded strain (ε_u) is strongly influenced by the choice of the instant of the manual stop of the.

Furthermore, in the *Figure 3.8* is shown stress-strain diagrams for tested Adobe samples.

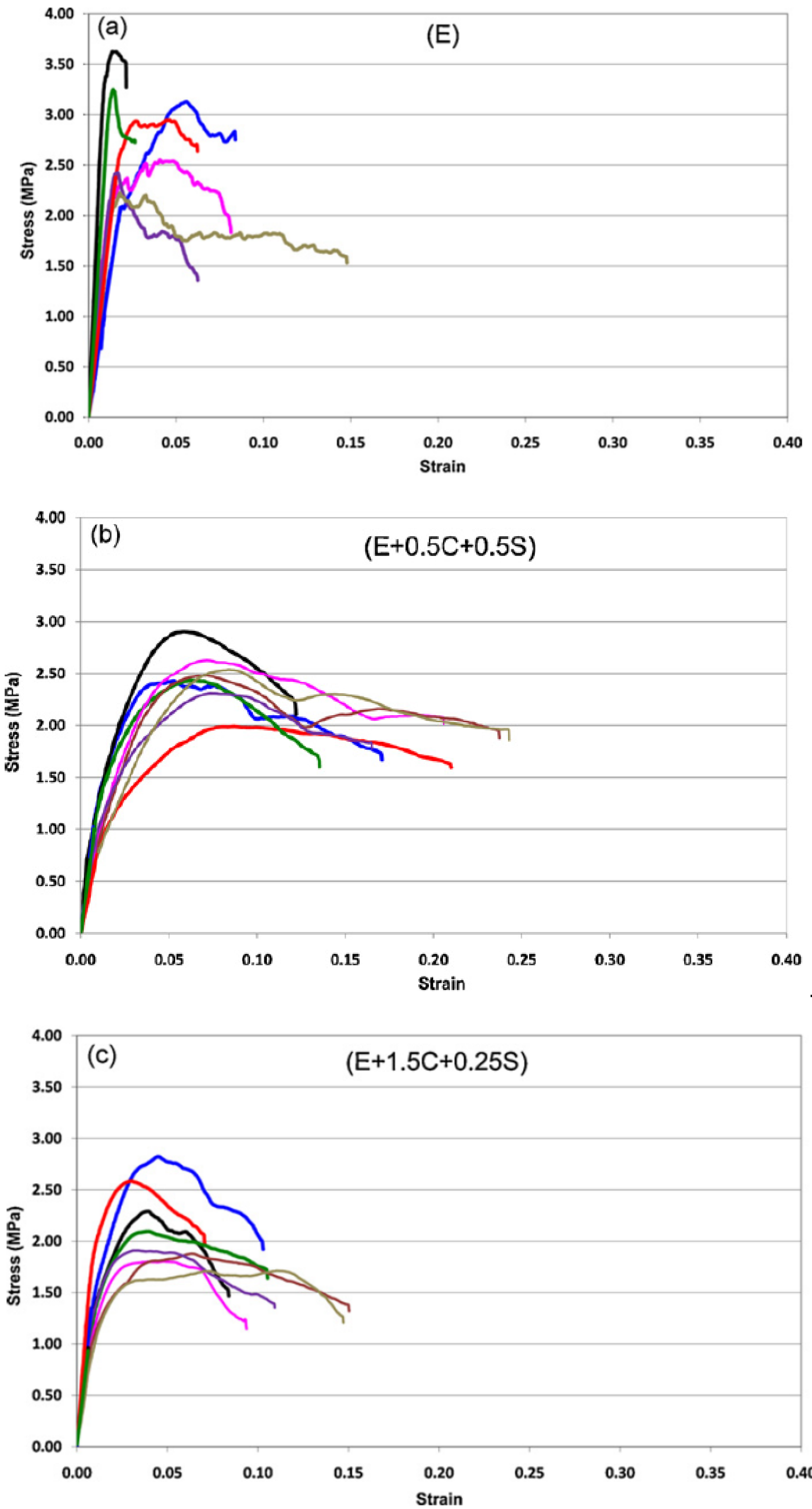
Name of mixtures	Clay (%)	Silt (%)	Sand (%)	Gravel (%)	Straw (%)	Water (%)
E	25.6	43.6	11.4	9.3	0.0	10.1
E + 0.5C + 0.25S	16.3	27.7	27.1	18.2	0.3	10.4
E + 0.5C + 0.5S	16.3	27.8	27.2	18.2	0.6	10.0
E + 0.5C + 0.75S	16.3	27.7	27.1	18.1	0.9	10.0
E + C + 0.25S	12.0	20.5	35.5	23.0	0.2	8.7
E + C + 0.5S	11.9	20.3	35.3	22.8	0.4	9.2
E + C + 0.75S	11.9	20.2	35.0	22.7	0.6	9.6
E + 1.5C + 0.25S	9.7	16.4	40.3	25.8	0.2	7.6
E + 1.5C + 0.5S	9.6	16.4	40.3	25.7	0.3	7.6
E + 1.5C + 0.75S	9.6	16.3	39.9	25.5	0.5	8.4

Table 2. Percentages of soil, coarse sand, water and straw fibers used in mixtures [12]

Name of mixtures	σ_{max} mean [MPa]	σ_{max} mean S.D. [MPa]	Lowest σ_{max} [MPa]	Highest σ_{max} [MPa]	E_{mean} [MPa]	E_{mean} S.D. [MPa]	$\varepsilon_{\sigma max\ mean}$	$\varepsilon_{\sigma max\ mean}$ S.D.	ε_c mean	ε_c S.D.
E	2.88	0.5	2.22	3.63	211	96	0.029	0.018	0.070	0.040
E + 0.5C + 0.25S	2.67	0.57	1.57	3.34	112	21	0.089	0.051	0.148	0.058
E + 0.5C + 0.5S	2.46	0.26	1.99	2.9	108	23	0.072	0.013	0.159	0.043
E + 0.5C + 0.75S	2.61	0.39	1.87	2.99	98	29	0.115	0.052	0.241	0.082
E + C + 0.25S	2.59	0.28	2.07	2.98	119	34	0.055	0.009	0.089	0.018
E + C + 0.5S	2.41	0.63	1.67	3.09	132	31	0.047	0.011	0.101	0.026
E + C + 0.75S	2.82	0.24	2.33	3.11	108	46	0.078	0.014	0.152	0.068
E + 1.5C + 0.25S	2.14	0.4	1.71	2.82	155	35	0.050	0.026	0.095	0.027
E + 1.5C + 0.5S	2.44	0.38	1.79	3.07	139	35	0.046	0.007	0.095	0.017
E + 1.5C + 0.75S	2.52	0.3	1.97	2.93	139	24	0.072	0.034	0.127	0.058

S.D.: standard deviation.

Table 3. Compression test results [12]



a) b) c)

3.8. a)-b)-c) compressive stress–strain diagrams for the tested samples [12]

6.1.5. The effect of coarse sand and straw on the compressive strength

It is instantly possible to note that the highest compressive crushing strength belongs to the E-mixture (alone earth) that reached 2.88MPa *(Table 3).* Straw is weakly adherent to the earth matrix, therefore, at the beginning of loading they can slip off and they may have an adverse effect on compressive strength. On the other hand, it is necessary to remember that only full earth bricks cracked during seasoning, on another different mixture samples no cracks appeared. Consequently, it is not possible to use only earth to produce large bricks.

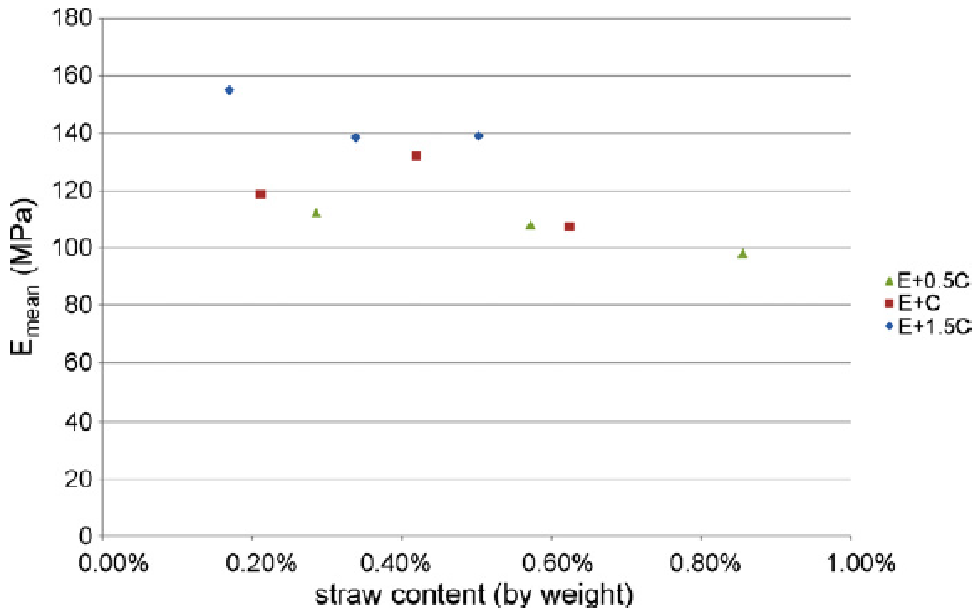
The lowest compressive crushing strength relates to the mixture that has the higher coarse sand content and the lower straw content (E + 1.5C + 0.25S), which is barely reached 2.14 MPa. Hence, the excessive rising of coarse sand into the mixtures (1.5 volume) seems to make the compressive crushing strength worse, especially if the straw proportion is low *(Table 3)*. But anyway, the effectiveness of the reinforcement is more noticeable with the high addition of coarse sand into the mix (poor clayey mix), that is to say, E + 1.5C-samples *(Table 3).*

If we consider contents by weight, according to the results of the experiment, the clay content of the mixture between 12 and 16% *(Table 2)* is preferable in bearing adobe structure elements, same values had Sukru Yetgin in his research [10]. Besides, it is clear that, a straw content range between 0.3 and 0.6 percent (0.5 volume) and it does not seem to affect compressive strength a lot, whatever the addition of coarse sand *(Table).*

5.1.6. The effect of coarse sand and straw on the Young modulus and on the strain

The average of the experimental Young modulus E_{mean} are reported in *Table 3*, too. E-samples (only earth) gave the highest value, although they had the highest standard deviation. The other bricks samples gave results comprised between about 100–155 MPa.

The volume increasing of coarse sand content into the samples practically always determines an increment of E_{mean}, independently by the straw content, as it can be seen in *Table 3*. If we consider contents by weight, decreasing amount of clay and straw always determine an increasing of E_{mean} *(Figure 3.9).* This effect is more visible especially when straw content is high (0.5–0.9%), with differences up to 40%. Therefore, the highest E_{mean} (155 MPa) belongs to the E+ + 1.5C + 0.25S-mixture, that has also the worst $\sigma_{max\ mean}$. This represents a trend that is always followed by almost all the samples.



3.9. The dependence of the Young modulus of the samples from the amount of straw. (by weight) [12].

Besides, the addition of straw fibers significantly affects to the "plastic" behavior of the samples. As the straw content increases, the "plastic" behavior can be clearly seen *(Figure 3.8),* especially if not too much coarse sand is added. This can be easily noticed from the control strain ε_C, too. At the same coarse sand and rising straw content always causes an increment of ε_C, that is shown in the higher values for low coarse sand additions (E + 0.5C-samples) and the lowest value for E-samples.

6.1.7. The effect of coarse sand and straw on the breaking manner

For E-samples (only earth) the final failure occurs almost immediately after the ultimate load and commonly in a brittle way with only large cracks *(Figure 4.1)*.

Breaking manners were similar in all samples and they do not seem to depend on composition. The areas near the lateral surface were crushed and fallen off. Consequently, vertical cracks appeared, particularly near the corners, sometimes connected with horizontal ones due to the bending of the detached lateral side.

The breaking of bricks has sometimes involved two of the four vertical sides of the samples, these sides belong to the external sides of the original brick. That is why this breaking way seems to depend on a productive process, that is on pressing mixture of Adobe into the mold. This is reasonably due to the fact that the core of each block is better manually compacted into the formwork, producing stronger core and weaker sides [12].

Furthermore, the increase of straw fibers causes the development of an elevated number of small width cracks at bricking *(Figure 4.2)*. This effect is more noticeable when the added volume proportion of coarse sand is low. This fact is probably a consequence of the bridging effect of the natural fibers, and it may be explained by considering the redistribution of internal forces from the soil matrix to the reinforcing fibers [12]. Likewise, it must be mentioned that the straw fibers hold together the soil matrix and no rupture of fibers seems to have occurred although a loss of fiber bond was detected. On the other hand, the failure of specimens with high straw reinforcement was more ductile, as it shown in *Figure 4.2*. In the end, E-mixture (only earth) had the worst ductile behavior, while the better ductile behavior belongs to the mixtures rich in clay and straw, such as E + 0.5C + 0.75S samples.

4.1. Breaking of a block belonging to the E-mixture (only earth). Cracks of this mixture typology were punctual and of large size [12].

<u>*6.1.8. Conclusion of the experimental program.*</u>

The aim of this experiment was to find which combination of raw materials have better influence to mechanical properties of Adobe. Below are the main results of experimental program:

- A preferable clay content into the adobe brick is between 12 and 16 % (by weight);

4.2. Breaking of a block belonging to the E + 0.5C + 0.75S-mixture. [12].

- All tested mixtures gave good compressive strength. From the experiment we can say that the compressive strength of typical Adobe brick is approximately 2.6 MPa. This value is not high as concrete or fired brick's strength, but still successful in construction of the one or two story buildings.
- Natural fibers, as straw, control the plastic behavior and impact to the breaking way of the Adobe specimen.
- The inclusion of straw into the mixture is very important, it prevents shrinkage cracks during the drying process.

6.2. Hygro-thermal properties of Adobe brick

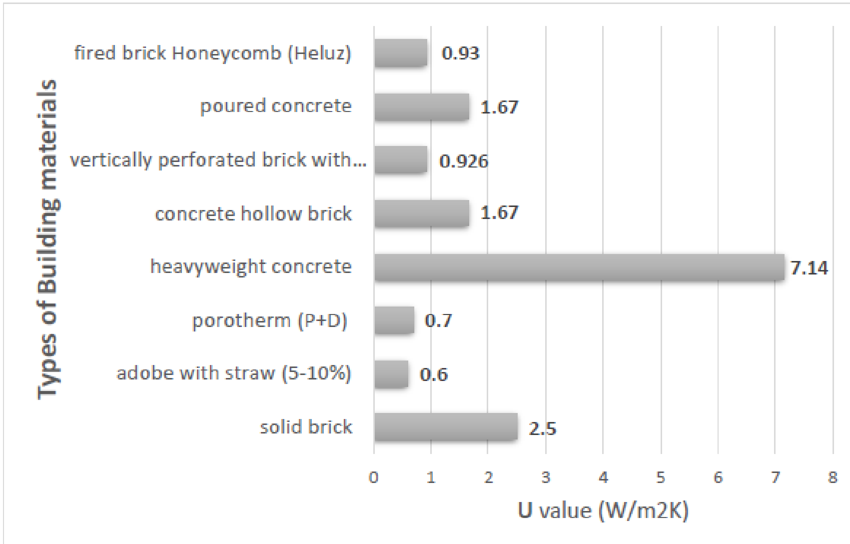
Adobe bricks became popular, not only for their mechanical properties, as shown above, but also for the comfort level of buildings made with earth. Because of its humidity balancing effect and high thermal capacity. The earth could store heat absorbed during the day, keeping the interior of the house relatively cool. When the outside temperature drops at night, the walls start to emit the heat stored during the day inside of the building. The specific heat capacity (c) of the adobe material is a key factor in its ability to moderate temperature peaks in buildings because adobe materials have relatively high thermal. This fact you can admit from the table below, where is shown thermal properties of 300 mm thickness wall from different materials, including the Adobe wall with 5-10% of the straw content.

walls without plaster	**thermal transmittance**	**thermal resistance**	**thermal conductivity**
	U (W/m^{2}K)	**R** (m2K/W)	**k** (W/mK)
solid brick	**2.5**	0.4	0.75
adobe with straw (5-10%)	**0.6**	1.67	0.18
porotherm (P+D)	**0.7**	1.43	0.21
heavyweight concrete	**7.14**	0.14	2.14
concrete hollow brick	**1.67**	0.6	0.5
vertically perforated brick with lightweight mortar	**0.926**	1.08	0.278
poured concrete	**1.67**	0.6	0.5
fired brick Honeycomb (Heluz)	**0.93**	1.075	0.279

Table 4. Thermal properties of 300mm thickness wall from varied materials [1,18,19]

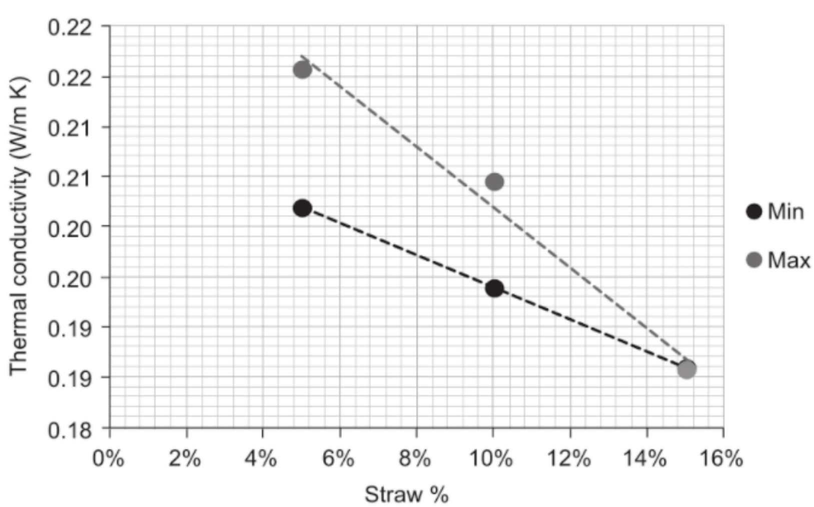
From the graph (*Figure 4.3*), we can see that nonindustrial Adobe brick has better insulation properties than some industrial building materials, which represents one of the advantages of eco-efficient construction.

In the *Table 4*, were written “Adobe with straw (5-10%)” has thermal conductivity 0.18 W/mK, however the amount of straw added to the soil to reduce shrinkage of adobe bricks does not influence in a strong way thermal conductivity. It can be seen in the *Figure 4.4*, which reports thermal conductivity of adobe brick with different straw percentages.



4.3. Thermal transmittance (U-value) of Adobe (with straw) wall in comparison with other materials in the thickness 300mm. (according to the Table 3)

Furthermore, the ability of adobe bricks to conduct heat also depends on the moisture content because of the strong relationship between water content and heat conduction. In moderate and hot climates, the moisture content of adobe bricks could be a benefit because of the phase transition of the water. When the material starts to dry, water evaporates; therefore, heat loss in the form of latent heat occurs, which in turn causes the external surface temperature to decline.



4.4. Relationship between straw and thermal conductivity [1].

Certainly, Adobe is not the best insulation material, but even a poor insulating material can insulate effectively if it is large enough and if it can “absorb” heat. In fact, some researches show that an adobe house can maintain natural thermal comfort a natural air conditioning effect because the temperature of rooms tends to be cool during daytime and warm during nighttime.

In the end, as was written before, Adobe walls have humidity balancing effects, thus, the earth structures have hygroscopic qualities. They balance the indoor climate by absorbing and releasing moisture as the relative humidity of the air changes. In fact, high moisture levels impact the thermal performance of the building and indoor air quality through the development of molds and bacteria. The recommended relative humidity for person’s comfort is between 40% and 60%, as mentioned by most of the scientists.

7.Durability of Adobe constructions

The durability of Adobe constructions is testified by the fact that some of these buildings last for hundreds of years. Usually, it depends on proper maintenance and repairs that are compatible with the original construction. In general, adobe structures may be protected by correctly designed the roof or protecting them i.e. plaster. Anyhow, water is the main potential disadvantage for adobe bricks.

In fact, adobe walls can be washed out under rain impact and collapse when exposed to continuous rain for several hours. Also, water absorption might cause the swelling of clay minerals whereas evaporation of water from the clay gives growth to shrinkage and cracking. For that reason, unprotected adobe walls suffer greatly from durability problems due to water erosion, evaporation, and penetration.

To improve the durability of Adobe brick, impregnation with soluble sodium silicate by water-based organic silicone emulsion has been tested. In general, the aim of the experiment was to raise the consolidation and waterproofing of the samples. In the end, the durability of the treated bricks was found to be expressively increased compared with that of the untreated ones. In addition, during the impregnation very low concentrations of both sodium silicate and silicone emulsion were used, and there were no organic solvents involved in the treatment. Therefore, the cost of the treatment was small and could be acceptable for increasing the durability of structures.

Several types of durability tests are proposed for earthen materials, obtaining dispersed results because of the variability of their technical test specifications [1]. However, recent studies have shown that these tests could be too severe and unrealistic because unstabilized earth brick could often not pass these tests whereas existing traditional unstabilized earth walls have undergone more than 100 years of weathering [1]. That is why the progress of new suitable durability tests accounting for, for example, the different climatic conditions are the main issue, and further studies need to be carried out. This might be also important to elect when the stabilization is needed.

Nowadays, the most common durability tests are the spray erosion test and the drip erosion test. They are mentioned for adobe bricks in several national standards.

The spray erosion test is usually referred to as a direct copy of the erosion originated by rainwater, studying its application in real conditions, whereas the drip erosion test is a good, cheap test for testing blocks in areas of little rain.

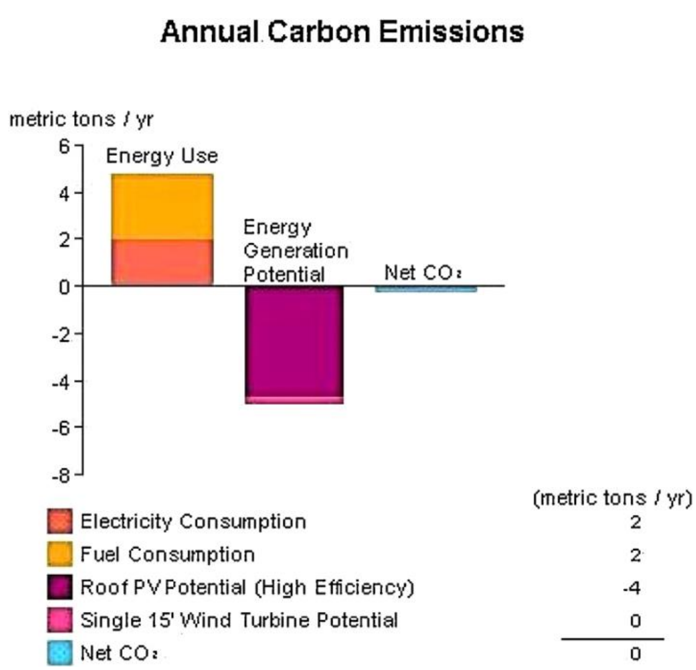
All tests are based on the same foundation of subjecting a test tube to a pressure spray for a certain amount of time or until the specimen is penetrated (spray erosion), or to a continuous waterfall for a certain amount of time (drip erosion), to evaluate afterward the damage caused in both cases.

8.Environmental impact of Adobe construction

The first impact of Adobe to the environment:

Global climate change has drawn significant attention to the building construction industry over the last few years. The building sector today is known to be consuming 40% of the world energy and in turn, supports 23–40% of the world's greenhouse gas emission, mainly CO2 [7]. According to scientists, the replacement of only 5% of concrete blocks used in the UK masonries by earth masonry would mean a reduction in CO2 emissions of approximately 100,000 tons [1].

Unlike modern buildings, earth related building materials (for example Adobe) have nearly zero carbon footprints. This phenomenon was proven by the Department of Architecture of Cyprus International University. They did research with an experiment about the environmental impact of the use of Adobe. In the experiment, a typical traditional Adobe building in Louroujina—North Cyprus, was simulated through a parametric computer based simulation done using Revit Autodesk - with a Green Studio Plug-in, a program which models the yearly carbon emission of the building and the yearly energy consumption. In the end, according to the data collected from the parametric simulation and owing to the rate of carbon emission per year shown in *Figure 4.5,* it can be ascertained that, Adobe buildings have zero footprints.



4.5. The rate of Carbon emission per year in Adobe building [7].

The second impact of Adobe to the environment:

Thermal properties of Adobe allow for walls without any additional thermal insulation materials like extruded polystyrene, the rigid foam of polyisocyanurate or polyurethane. These insulation materials are associated with severe impacts in term of toxicity. Polystyrene, for example, contains antioxidant additives and ignition retardants. Moreover, its production involves the generation of benzene and chlorofluorocarbons. However, polyurethane is obtained from isocyanates, which are releasing toxic fumes when subjected to fire. Also, isocyanates are widely known for their tragic association with the Bhopal disaster (in 3.12.1984).

The third impact of Adobe to the environment:

Earthen buildings like Adobe may help with deforestation problem (*Figure 3.7*). For example, in Ethiopia (Africa), hundred years ago, there were a lot of forests**,** which were our primary material resources for building constructions. But, nowadays, forests are almost gone, and woods for constructions are rare. There are various methods which are appropriate and reliable for controlling deforestation. One of these methods is minimizing consumption of resources that have direct contact with forests. This consist of materials which are used in building construction**.** In order to tackle the problem, an idea of low-cost building construction, based on earth as the main building material, was developed. So, one of the deforestation solutions is to replace wooden mud houses by only earthen blocks (adobe), which would help to restore the ecological balance and to build a house with high quality and with a fair price.

Ending deforestation is one of the quickest and most cost-effective ways to curb global warming.

The forth impact of Adobe to the environment:

In most cases Adobe bricks don’t need to be transported from one place to another. That is one of the reasons why Adobe bricks are less pollutant than another building materials, the material used in the construction is placed in-situ. This issue may give no sense but, costs derived from transportation cannot be avoided, and neither can be the pollution caused by them.

4.6. Deforestation in Africa [22]

The fifth impact of Adobe to the environment

Adobe bricks, as another earthen material is fully recyclable, which means zero waste to our planet. It is a positive way for the brick industry to contribute to a more eco-efficient construction. This option not only prevents an increase of the area needed for waste remove but most significant, avoids the exploitation of nonrenewable raw materials used in the production of masonry units. As a result, the fully recyclable material is reducing environmental impacts such top soil loss, air pollution and pollution of water reserves. At the end of Adobe building's life, the earthen brick can be easily reused by grinding or wetting, or it can be returned to the ground with no environmental hazard involved; in fact, it is able to be returned to its initial state (as a soil) by simply wetting. Even when the soil is stabilized with cement or lime, it could potentially be reused for this type of construction, even if this is not a unanimous standpoint in the literature (Earth construction: a comprehensive guide) [1].

9.The impact of Adobe walls to indoor air

The first advantage of using adobe bricks could be associated with *detoxifying effect* (the ability to absorb toxins and smells from the indoor air). It is most relevant to volatile organic compounds in the building. Because volatile organic compounds (VOCs) include a variety of chemicals, some of which may have short- and long-term adverse health effects [9].

The second advantage of adobe bricks is related to their ability in moderating changes of indoor relative humidity. An unburnt brick is, in fact, much superior to burnt brick as a humidity buffer, and its hygroscopic behavior can be more efficient in reducing the indoor air relative humidity than the use of ventilation. Some investigations show that earth brick can absorb ten times more weight moisture than ceramic bricks and that an earth construction can keep the relative humidity of indoor air between 40 % and 60 %, which is the optimum range for human health.

10.Adobe is a key of better life. Shelter problems.

Nowadays, the majority of developing countries are faced with a problem of providing adequate and affordable housing in sufficient numbers. Because of the rapidly increasing population, in the last few decades, shelter conditions have been worsening: resources have remained scarce, housing demand has risen and the urgency to provide immediate practical solutions has become more sensitive. Adequate shelter is one of the most momentous basic human needs. Nevertheless, 25% of the world's population does not have any permanent home, and 50% of the urban population lives in slums. And it is true that, 80% of urban settlements in developing countries consist of slums and spontaneous settlements made of temporary materials (plastic sheets, flattened cardboards).

Around 100 million people around the world are homeless (2005) [27]. Sub-Saharan Africa has the world's highest annual urban growth rate (4.58%) and highest slum growth rate (4.53%) [27]. These numbers are frightening, and they are remaining unchanged.

From early stages, Egyptians tried to use Adobe sunbaked bricks instead of baking bricks. Baking bricks were very expensive material for the Egyptians because of fuel, which was scarce to begin with, and the need for a better mortar than the usual cob binder. As Egyptians, people with shelter and cost problems, can choose Adobe brick as a building material. Even if people do not have money to buy the adobe blocks, they can make it by themselves, because the techniques of manufacture are very simple. Also the adobe brick wall has nearly the same properties as an insulated brick wall, which costs considerably more than locally produced adobe brick of equal size.

In the end, by using adobe bricks, an economic impact may be also pursued: The slight cost of raw material, local skills and employment can be developed because of their simple manufacturing, and auto-construction can be promoted [1].

11.Conclusion.

Based on this research, I arrived at several conclusions:

- Adobe brick is one of the earliest building material in the world and still in priority;
- Adobe constructions are popular not only in countryside areas but also in urban places and you can find them in every continent of the planet, except Antarctica;
- The composition of Adobe brick consists only of raw ingredients, which makes it 100% eco-friendly material. The components of adobe brick, in fact, can be considered as analogous to those of concrete: the inert aggregate fraction is represented by granular soils (sand and gravel), and the binder fraction is represented by cohesive soils (silt and clay). The inclusion of straw into the mixture is very important, it prevents shrinkage cracks during the drying process.
- Adobe will not need a large amount of energy for its production and application, because they don't need treatment. The time for producing earth brick is during spring or autumn because the sun is not much strong and so there is not a rapid drying process that can produce cracks. The shape of the brick does not have any restrictions, and it can be various.
- The Adobe brick does not get mechanical strength as high as concrete or burnt brick. However, the Adobe is strong enough, ductile and resistant against earthquake. And the compressive strength of typical Adobe brick is approximately 2.6MPa (from the experimental program)
- Adobe walls have the ability to absorb and store up heat and subsequently release this heat when it is necessary. It is because of their high thermal capacity. Also adobe brick wall has the nearly the same U-value as insulated brick wall. Thermal properties of Adobe help to keep healthy indoor air by absorbing toxins and smells.
- Adobe buildings have a good durability.
- The main disadvantage of adobe walls is that they can be washed out under rain impact and collapse when exposed to continuous rain for several hours.

- Adobe bricks are fully recyclable, have nearly zero carbon footprints, and can be solution against to global warming and deforestation
- In conclusion, I want to say that all earth building techniques are very important in today's world. They give a huge opportunity for better life, with solving ecological and shelter problems and by improving them, we can facilitate our future.

12.References

[1] F. Pacheco-Torgal, “Eco-efficient Masonry Bricks and Blocks: Design, Properties and Durability”, Oxford, UK, (2015). https://books.google.cz/books?id=KdU6BAAAQBAJ&pg=PA375&lpg=PA375&dq=Houben+H,+Guillaud+H.+Earth+construction:+a+comprehensive+guide.+London:+ITDG+Publishing;+1994.&source=bl&ots=IWu_m8i9Cc&sig=j2SfqKJSs6BgxjMzM6s4OdPe4XI&hl=ru&sa=X&ved=0ahUKEwic2NP8hIbTAhUFhywKHawJCrQQ6AEIITAB#v=onepage&q&f=false

[2] Gernot Minke, “Building with Earth”, (2006). https://ia800306.us.archive.org/13/items/Gernot_Minke-Building_With_Earth/Gernot_Minke-Building_With_Earth.pdf

[3] Auroville Earth Institute, “A Millennia old tradition”. http://www.earth-auroville.com/world_techniques_introduction_en.php

[4] https://en.wikipedia.org/wiki/Adobe

[5] ROBERT S. HOMSHER, “Mud Bricks and the Process of Construction in the Middle Bronze Age Southern Levant”, (November 2012). https://www.researchgate.net/publication/259748510_Mud_Bricks_and_the_Process_of_Construction_in_the_Middle_Bronze_Age_Southern_Levant

[6] David Gandreau and Leticia Delboy, “World heritage Inventory of earthen architecture”, (2012). http://unesdoc.unesco.org/images/0021/002170/217020e.pdf

[7] A.P. Olukoya Obafemi and Sevinc Kurt, “Environmental impacts of adobe as a building material: The north Cyprus traditional building case”, Cyprus, (June 2016). http://www.sciencedirect.com/science/article/pii/S2214509515300176

[8] Marcial Blondet, “Earthquake-Resistant Construction of Adobe Buildings: A Tutorial”, Peru, (April 2011). http://www.world-housing.net/wp-content/uploads/2011/06/Adobe_Tutorial.pdf

[9] “Volatile Organic Compounds. Impact on Indoor Air Quality”. https://www.epa.gov/indoor-air-quality-iaq/volatile-organic-compounds-impact-indoor-air-quality

[10] Sukru Yetgin, “The effects of the fiber contents on the mechanic properties of the adobes”, Turkey, (March 2008).
https://www.researchgate.net/publication/229282299_The_effects_of_the_fiber_contents_on_the_mechanic_properties_of_the_adobes

[11] C.H. Kouakou and Jean-Claude Morel, “Strength and elasto-plastic properties of non-industrial building materials manufactured with clay as a natural binder”, France, (April 2009).
https://www.researchgate.net/publication/240433928_Strength_and_elasto-plastic_properties_of_non-industrial_building_materials_manufactured_with_clay_as_a_natural_binder

[12] Enrico Quagliarini and S. Lenci, “The influence of natural stabilizers and natural fibres on the mechanical properties of ancient Roman adobe bricks”, Italy, (July 2010).
https://www.researchgate.net/publication/248546225_The_influence_of_natural_stabilizers_and_natural_fibres_on_the_mechanical_properties_of_ancient_Roman_adobe_bricks

[13] “How to make Adobe brick”, http://www.doityourself.com/stry/how-to-make-adobe-brick

[14] video, “Adobe Brickmaking Process”, (2014).
https://www.youtube.com/watch?v=uWBz9kl-hTA&t=6s

[14] Richard Coffman, “Adobe mineralogy: Characterization of Adobes from around the world”, (January 1990).
https://www.researchgate.net/publication/215759035_Adobe_mineralogy_Characterization_of_adobes_from_around_the_world

[15] “Mud Architecture - Construction Details and Techniques”,
http://www.archinomy.com/case-studies/712/mud-architecture-construction-details-and-techniques

[16] Edward Avery, “An Investigation into the Use of Dynamic Compaction for the production of Adobe Bricks”, (April 2014)
https://www.researchgate.net/publication/262260508_An_Investigation_into_the_Use_of_Dynamic_Compaction_for_the_production_of_Adobe_Bricks

[17] Mohammed Ali Bahobail, “The mud additives and their effect on thermal conductivity of adobe bricks”, Kingdom of Saudi Arabia, (January 2011).
https://www.researchgate.net/publication/264901096_The_mud_additives_and_their_effect_on_thermal_conductivity_of_adobe_bricks

[18] Protherm brick properties.

http://www.fce.vutbr.cz/PST/danek.l/BH52_prednasky/BH_52_02.pdf

[19] thermal resistance of building materials http://www.movida-project.eu/files/17_thermal_resistences%20D27.pdf

[20] Faycal El Fgaier, “Thermal performance of unfired clay bricks used in construction in the north of France: Case study”, France, (September 2015).
http://www.sciencedirect.com/science/article/pii/S2214509515300097

[21] M.C.J. Delgado, I.C. Guerrero, “Earth building in Spain”, Spain, (April 2005).
https://centrocidart.files.wordpress.com/2013/10/sdarticle.pdf

[22]https://www.google.cz/search?q=deforestation+in+africa&rlz=1C1CHBF_enCZ744CZ744&tbm=isch&tbo=u&source=univ&sa=X&ved=0ahUKEwi234jhkpPUAhUNIlAKHWAFAu8QsAQIOA&biw=1198&bih=1113

[23]https://www.google.cz/search?q=Fortified+city,+Draa+valley,+Morocco&rlz=1C1CHBF_enCZ744CZ744&tbm=isch&tbo=u&source=univ&sa=X&ved=0ahUKEwjGjeDhk5PUAhWGblAKHQTQBaMQsAQIJg&biw=1198&bih=1113#imgrc=ZpvTfNz03Xa1ZM:

[24]https://www.google.cz/search?q=Citadel+of+Bam,+Iran,+before+earthquake+of+Dec.+2003&rlz=1C1CHBF_enCZ744CZ744&tbm=isch&tbo=u&source=univ&sa=X&ved=0ahUKEwjigY6ElJPUAhVJZ1AKHQZnA1IQsAQIJg&biw=1198&bih=1113#imgrc=TpcipwEg-QKVEM:

[25]https://www.google.cz/search?q=Sizes+of+soil+particles.&rlz=1C1CHBF_enCZ744CZ744&tbm=isch&imgil=tWup7RTSqBOhRM%253A%253BC74TO3KXK2FAcM%253Bhttps%25253A%25252F%25252Fschool.discoveryeducation.com%25252Fschooladventures%25252Fsoil%25252Fname_soil.html&source=iu&pf=m&fir=tWup7RTSqBOhRM%253A%252CC74TO3KXK2FAcM%252C_&usg=__HBTe2StBOIzTfGFf1jpCM3-

5OxQ%3D&biw=1198&bih=1113&ved=0ahUKEwiA4uWalZPUAhWMIlAKHbZ6CMAQyjcIRQ&ei=5g8rWYDXCIzFwAK29aGADA#imgrc=tWup7RTSqBOhRM:

[26]https://www.google.cz/search?q=sand+silt+clay&rlz=1C1CHBF_enCZ744CZ744&tbm=isch&tbo=u&source=univ&sa=X&ved=0ahUKEwiT6p3AlZPUAhWKLVAKHZ2eB_AQsAQIJg&biw=1198&bih=1113#imgrc=h7Qa20HqbM2xSM:

[27]https://www.google.cz/search?q=straw+fibers&rlz=1C1CHBF_enCZ744CZ744&tbm=isch&tbo=u&source=univ&sa=X&ved=0ahUKEwiIspnVlZPUAhWPalAKHeylCvMQsAQIMQ&biw=1198&bih=1113#q=straw+fibers&tbm=isch&tbs=rimg:CVYeVw5lhP90IjiLN-V6ViogPiq77omTJOyOEQYd6jsWPwxBhzFM8H2SoWjDvVXH0mi9g2kQKwlYgU8eTCuPbeawsioSCYs35XpWKiA-Efj5Q_1exypNQKhIJKrvuiZMk7I4RHHnBGlb_1ST8qEgkRBh3qOxY_1DBHMBunnYHePByoSCUGHMUzwfZKhEWtY0ry11wZRKhIJaMO9VcfSaL0R9ExGadAbrgMqEgmDaRArCViBTxGAhC4YZLEjdyoSCR5MK49t5rCyESDRFakcHlNj&imgrc=EQYd6jsWPwwJ9M:

[27] http://www.sharing.org/information-centre/articles/shelter-key-facts-and-resources