OPTIMIZATION IN ENGINEERING ASPECTS OF CONSTRUCTIONS WITH EARTH BY LABORATORY TESTS.

A proposed methodology for the proper soil.
Examples of modern houses built with earth in Greece.

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Index

Figure catalogue

1 Introduction

1.1 The earth as building material

Earth is one of the most abundant, most locally available, cheapest and lowest energy input impact materials it's possible to build with.The energy required to dig up and treat sufficient earth for a house, was all provided by humans and animals. Nowadays, mechanical extraction and mixing is the more likely method, but assuming the earth is sourced fairly locally to the site, it is still a very low-energy form of construction.Earth is a 100% eco-friendly building material, neither it is manufactured nor transported.Over 70% of landmass is either pure clay or laterite- clay (with some iron content). A wall made from raw earth serves as a natural air conditioner, being warm in winter and cool in summer. When the building is demolished, the earth returns to the soil and can be recycled indefinitely. Currently it is estimated that one half of the world's population – approximately three billion people lives or works in buildings made of earth.

There are a number of advantages in construction with earth:

-soil as a building material has little or no energy consumption for its manufacture and transport.

-there is possibility of complete recycling clay and biodegradation of materials mixed with it.

-the creation of environmentally friendly environment: clay does not release substances harmful to the body like many artificial materialsdo while at the same time it has the capacity to balance the moisture content of space.

-has good integration of the constructions into the natural landscape.

Earth buildings have been created since ancient times, but the use of modern materials with standardization and better mechanical strength has placed this technique on the sidelines of modern construction.

In Greece, constructions made of earth (mainly raw bricks) have a history of at least 7000 years, from the Middle Neolithic period, until the late 1960s, when the clay was out placed by modern materials.

Due to the fact that this material is not standardized and there is no industrial process to support it in order to create a construction from earth, we must perceive it as a digest consisting of:

1. Clay (cement mortar)
2. Slit (extremely fine)
3. Aggregates (sand, gravel)
4. Water (which is needed to make the mortar workable and easily shaped).

In this context, we can control the earth mortar that we will be preparedfor use.

There are several empirical methods (Sargentis 2010) and many laboratory tests (Minke 2008) to determine the proportion of raw materials which can be addedto the earth mortar but the aim of this work is to present the material as a common, free material, easy to find at its site, all over the world when needed a solution for construction. In this research we also present the appropriate laboratory tests for constructions with earth.The tests examine the "proper" waterneeded to produce a reliable earth mortar which will be tested by preparing samples that will be broken in 28 days, at 3 and 6 months at laboratory apparatusto ascertain the mechanical strength.

1.2 What we optimize with this task

Soil was a basic building material as part of the load-bearing system of a structure oras a filler element (masonry) and also used asfinal layer of the construction (roughcast).It's been used in traditional constructions, in building restorations as a basic building material.

Its abundance in nature and its ecological context have provoked the interest of people in recent years in its use in modern architecture. Also structures made of earth are healthy for humans and for planet and also they are an essential part of sustainability.

The construction systems based onearth,like adobe and wooden frame structure, well known in traditional architecture globally, came back to the forefront, since its inception by n-ZEBi and Deep Green constructions.(net-zero energy building, is a building with zero net energy consumption, meaning the total amount of energy used by the building on an annual basis is roughly equal to the amount of renewable energy created on the site,[1][2] or in other definitions by renewable energy sources elsewhere.

1.3 Earth as Commons and its Social dimension

Moreover, due to the ease of supply, use and application of the material, the products of this architecture have also been described as "architecture for the poor" (Fathy 2010). A construction with earth is a process described of its very easy, fast, economic and ecological features. Earth is one of the most abundant, most locally available, cheapest and lowest impact materials it is possible to build with.

So modern construction thinking and "Low-Tech architecture" updated earth's technique and earth has become a basic material for the optimization of ecological architecture. In the next chapter we present the most common earth building techniques.

Compressed earth blocks and rammed earth are common techniques in many areas of the world. Building with earth or earth blocks, requires a little or no special skills which can be easily shared between constructors. The process is labor-intensive and the work is often heavy, but it can be phased to suit both the weather and the availability of helpers. In this report we investigate the different properties of earth with the aim of promoting it's construction technique.

The construction with earth isn't extensively used around the world. Some of the reasons for that are:

- Research about earth is quite new field compared with other more traditional construction materials like concrete and steel.
- One of the major reasons is likely to be a lack of knowledge.
- Lack of understanding the material's structural properties.
- The fact that there is no industry to produce technical materials to support it has contributed to its devaluation.
- In most countries, there is no building code for earth buildings. An unregulated construction technique discourages many possible users.

In exception,there are areas where earth construction is popular and traditional. For example in Australia, where owner-builders have elevated 'muddies' into something of an art form, making one house of mud bricks often done by a huge communal gathering over a weekend.

Earth buildings can withstand the tests of time, intensive usage and climatic change. It is an alternative to 'building with industrialized materials" both in terms of the energy, because non-renewable resources used for its preparation for construction and also about the comfort and thermal efficiency of the built house.

In addition, China's Xi'an University of Architecture and Technology has developed a project to help rural communities build new houses using both traditional and modern rammed earth technique. The project has successfully helped the local population to create entire new villages built with rammed earth. [1]

1.4 Ecological behavior

Earth is a sustainable and cost-effective construction technique. There are several benefits of using earth as a building material in constructions.

It is a low cost technical solutions for periods of financial or climate crisis. Also in remote areas, building with local soil means significantly reducing the costs of transporting to the site, materials for the construction.

In general, only one experienced builder is required on site to instruct workforce about how to construct the formwork and mix the materials. The rest of the work can be done by untrained or unskilled workforce, people from the local community. In this wayjobs are created and the costs of transporting workers from elsewhereis reduced.

The use of locally available and indigenous earth materials has several advantages in terms of sustainability as:

- Reduction of energy costs related to transportation.
- Reduction of material costs due to reduced transportation costs, especially for well-established industries.
- Support of local businesses and resource bases.

In general, constructions withearth involves a very low energy input, and creates virtually no pollution, because the energy required to dig up and treat sufficient earth for a house, was all provided by humans.

Figure 1.1 Soil with clay

[1] (http://theconversation.com/cheap-tough-and-green-why-arent-more-buildings-made-of-rammed-earth-38040) April 29, 2015, Daniela Ciancio, Senior Lecturer, Civil, Environmental and Mining Engineering, University of Western Australia

2 Different Constructions Techniques with Earth

2.1 Introduction

"Low-Tech Architecture" is an architecture that focuses on creating architectures that avoids using "technology" at every stage in the life cycle of the procedure (manufacturing method, materials, and use of construction).
In general, behind every building material is "hidden" technology and energy is required to be produced and transferred to the place of use.Thus, each material has a cost related to the energy, economic and environmental factors.The criterion of "Low-Tech architecture" is to avoid the use of high-tech and of energy consumption, as well as to minimize economic costs. It is important for sustainability to build with materials without consuming energy for their production, transport, also to be available in nature, to have the least amount of processing, or to come from reuse / recycling in order to have the minimum financial cost.
Depending on the area, the climate and the raw materials availableon the site, Low-Tech architecture is also guided by the construction traditions of each site where "interesting" technical proposals and solutions can be hidden.
With regard to our own region, a characteristic expression of "Low-Tech architecture" is architecture with the earth, which had a wide field of application in the 19th and early 20th century that today has been disregarded.

2.2 Brickwork- Adobe

One of the most popular constructing techniques with earth is adobe. The word "adobe" is Spanish, but its etymology derives from an old Arabic word, al-tob or al-tub, meaning "brick."Today, this material is gaining new popularity as a low-cost, environmentally friendly way of building. Adobe is nothing more than simple bricks made of sun-dried mud. Additionally adobe's mass helps keep buildings naturally cool in summer and warm in winter, reducing the need for cooling and heat.
Mud and straw are molded into a mold that dries in the environment (avoiding rapid drying in the sun). They can be made from most types of sub-soil. Enough clay is required to bind the mix together.The resulting structural element is a solid brick, which is also called adobe.The blocks are then laid and bonded with a mud and lime mortar and rendered with a mud or with plaster.It is simple to make and therefore appropriate for unskilled labor. They can be produced all at once, or in small batches, as and when time permits.
This kind of brick has been used in various areas in Greece in earlier times. In areas like Florina, Korestia in Kastoria Prefecture, Ilia and the Thessaly plain, the adobe houses were an ordinary building.
During the Asia Minor Catastrophe, adobe buildings were the technological answer for housing millions of refugees.It still exist some of the old buildings constructed for refugees that have remained in a good condition and were made of earth bricks, in the centre of Athens.

Figure 2.1: A brick house in the area of Palaio Faliro, city of Athens

Figure 2.1 Workshop for adobe bricks organized by “Πηλοίκο¨ (Piliko) team, Crete

Figure 2.2 Wall in wooden frame made from adobe bricks with roughcast(Piliko) team

Figure 2.3: Interior wall made of adobe. European Sustainability Academy in the area of Apokoronas, Crete. Photo E. Frangedaki

Figure 2.4: Experimental adobe bricks produced in the laboratory

2.3 Wooden frame walls (-Wattle &Daub)

Wattle and daub is a technique constructed with a lattice of vertical studs and horizontal wattles, woven together like a basket. A mud of earth and straw is then daubed onto latticework, forced into the gaps and smoothed over to fill any gap. The final surface can be left as a rustic finish or rendered with earth to make a smoother surface.Wooden skeleton more rarely is made of flexible tree branches.

The surfaces are coated with a spatula or with mud with straw or hair, hay or other fibrous materialsfor reinforcement and better adhesion to the substrate.With this technique, partition walls and external wall partitions are mainly constructed. This kind of wallisa non load-bearing system asit's been built into a light wooden framework. The thickness of the wall can range from 150 to 200 mm so this makes the technique ideal for dividing interior spaces.

When the construction is reinforced with diagonal elements and is properly connected with the other building elements, it gives rise to earthquake resistance. Sometimes lime mortar is used to seal the spaces between wooden sections in walls.This kind of walls is used in many buildings of traditional architecture (like traditional buildings in Pelion in Northern Greece).

Figure 2.5: Wattle & Daub wall constructed in the laboratory of NTUA.

Figure 2.6: Structures by Piliko team (photo E. Frangedaki)

2.4 Fermented clay (cob)

The'cob' consists of earth, shaping lumps of (clay) earth, stacking them up to form walls. Plinths of cob are stacked on top of one another and lightly tapped with hands or feet to form monolithic walls. The earth is reinforced by addedfibers, usually straw from various types of cereal or other kinds of vegetable fiber.

They are placed as a "sloppy" soft brick, one above the other. The dough of earth is "kneaded" -increased, creating a monolithic structure.

This technique began in Western Europe and has no traditional building blocks in Greece although it was widely used for the construction of auxiliary structures such as ovens and so on. Today many groups and collectives are active in its dissemination.

2.5 Rammed earth (Concrete earth)

It is also known by the French term "pisé de terre". Moist, loose earth is compacted in layers shuttered in a wooden mold of suitable dimensions.After the condensation, when the material has dried-solidified, the mold is removed along or upwards, to form a whole wall. The exact composition of the soil and the right portion of water are critical for the success of this method. Over a period of time, perhaps up to two years, a rammed earth wall will dry out and become as durable as sandstone.

This technique began in Western Europe; it has no broad "traditional" foundations in Greece. However, due to the fact that it creates structural elements with excellent texture, it has been observed that there is a general tendency to search for its application in modern architectural constructions.

Figure 2.7: Rammed earth by Piliko team (photo E. Frangedaki)

Figure 2.8: After 5 years without rain protection), Piliko team (photo E. Frangedaki)

2.6 Earth bags

Sacks are filled with earth, material usually available on site. When moist subsoil contains enough clay it becomes very cohesive when tamped.

The sacks are placed in the same way (like large bricks) and are compressed. Bare-wire is placed between the sacks. The wire mesh is "tangled" with the sack and stabilizes the structure (it works like the mud in the usual brick).The walls can be curved or straight, domed with earth or topped with a roof.

This technique was first applied to the great fortifications of the First World War and for temporary flood-control because it is quick and easy to create stable constructions.Today there is a tendency to find application in cheap construction (Sargentis 2009, Khalili 1998, Khalili 2008).

2.7 Light-Clay with Straw

Also called slip straw. Clay is mixed with water, and then is mixed with loose straw until every straw fiber is coated. It is another natural building material used to infill between a wooden frame in a timber framed building using a combination of clay and straw, woodchips or some other lighter material.The clay with straw is placed in wooden surfaces that form temporary molds. Once dry, dense clay-straw can be directly plastered with earth or lime plasters.

2.8 Other techniques with earth

In addition to the above constructions with earth, a variety of techniques have been invented so that the “earth” is placed into various types of "molds" which may eventually be incorporated into the structure itself. Thus, plastic bottles, used tires etc can replace bricks and become a cheap house building material. Also there are stabilized earth blocks. These are earth blocks made harder and more durable by the addition of small amounts of lime or cement (about 5%).

Other materials which can be combined with earth are straw bales, various scrap materials recycled materials, that they can create a shell thatforms the required space.

In Crete there are several examples of new buildings constructed by combining earth building systems. A new building in Nio Chorio, Crete, has 30cm thick external walls which have been built with light clay of ~500kg/m³ weight. A secondary wooden frame has been used during construction of the light clay walls in order to hold the mold and to decrease the distances between columns. The internal walls have been built by mud bricks that have been produced by the workers on site and dried in the sun.

Figure 2.9: Light clay Structure by Piliko team (photos E. Frangedaki)

Figure 2.10: Light clay interior wall with mud plaster

2.9 Regulations and adaptation to Greek legislation

While unmanufactured structures are accepted as load-bearing structures by regulations of other countries (such as New Zealand), they are not included in Greek regulations and are not accepted as load-bearing structures.

Therefore, these constructions require another, independent load-bearing structure that will certainly carry the construction loads.Generally it has been observed that usually at the interfaces between the “earth” and the concrete or the metal there are cracks and failures, and each construction member generally operates independently of each other. Instead,

natural materials such as wood have proven to be able to work better with “earthtechniques” so that they work cooperatively within a structure.
It is noted that in order to operate the earth as a building material, it is necessary that there it is no wetted by the rain water nor that it is affected by the rising soil moisture because in such a case the material will be plasticized, and construction will fail.

3 Environmental behaviors

3.1 General

Assessing the environmental behavior of structures with earth, we can discern the following characteristics:

The material is abundant in nature, has very low energy consumption at the stage of preparation for the construction (little integrated energy), it does not exhibit toxic behavior, is highly recyclable, has a high thermal mass, regulates indoor humidity and has a small ecological footprint.

3.2 Abundance in nature

The most of thw times it does not require some extraction or other activities that would cause environmental problems at the stage of collection. Nowadays, mechanical extraction and mixing is the more likely method, but assuming the earth is sourced fairly locally to the site.

3.3 Small integrated energy

Earth as a building material does not require any industrial steps to process it, or some energy to form as a material, unlike ordinary materials that require energy to produce it. So it is very efficient to use earth tecniques when the constructor is concerning the total energy consumption of the building.

3.4 Toxic behavior, gaseous pollutants

Fossil earth does not show toxic behavior either during collection, processing or use.It is extremely user-friendly material and also an unskilled worker can use this material without fear (Edwards 2000, Minke 2000).Throughout its life cycle, there is no procedure for the appearance of gaseous pollutants except if the transfer is required.

3.5 Recycling

The earth is a material that is recycled 100%.Recycling is extremely easy especially when it is crushed and wet.It is noted that no energy is required for its recycling.

3.6 Indoor conditions

Earth is a material with a high thermal mass. Due to this, its proper placement in the construction functions as a heat storage and regulator of the shell's internal temperature.Due to the fact that earth is a permeable material from moisture, it has the property of regulating the humidity of the interior.For the above reasons, it has been found that shells with earth create conditions of thermal comfort with little support.

4 Raw materials in earth mortar

4.1 Soil

The first thing we look at when making a mortar, is the basic raw material and in our case is the earth.Generally, the main components of the soil are clay, silt and aggregates.

4.2 Clay

Clay is a fine, chemically active soil with components (<0.002 mm diameter), which act as a natural adhesive in the clay mixture.Due to clay, the soil absorbs and retains large quantities of water. When the water evaporates, the soil solidifies and exhibits cohesion, mechanical strength and excellent physical properties.

4.3 Slit

Fine-grained, chemically inert soil components are sludge (0.06 - 0.002 mm in diameter), which only absorbs small amounts of water.Its effect is to reduce the friction between aggregates during the condensation process.The slitincreases the grain stability of the sand as it fills the gaps between them and has no adhesive properties.

4.4 Inert materials

Coarse, chemically inert soil components are gravel (diameter> 2 mm) and sand (2 - 0.06 mm in diameter).These come from rock breakage or river banks.They are components inert and stable, they do not absorb water and do not bind other chemical materials.They assure the strength of the mixture under pressure and greatly reduce the degree of shrinkage of the clay building blocks during drying incontrast to the clay (after it dries) and the grains of sand and gravel, which have a constant volume, prevent the shrinkage of the geogrid.

4.5 Normal water

For the proper composition of the mortar and the activation of clay it is necessary to add water to the mixture.The water to be used in the mortar must meet the requirements of workability of the mortar but also it has to be more than normal because it affects its cracking and ultimately the strength of the material.

4.6 Other Additives

To improve the properties of the material, other ingredients such as straw, hay, lime, cow slurry, etc. are added to the mix.It should be noted, that any material added to the mortar alters the mechanical and thermal properties of the material as well as the behavior of the material and the amount ofthe proper water and therefore requires further investigation.

5 Laboratory tests

5.1 General

Depending on the construction we want to make, the corresponding laboratory tests and the results we accept are also adapted. Thus, different requirement is for a building material when it is applied e.g. for the construction of masonry and different needs (high mechanical strengths) are when considered for coating construction (minimum drying shrinkage).

5.2 Clay

Clay is the welding material in the mortar of the earth.Clay holds your mortar together just like the cement in a concrete block.The clay connects the aggregates and creates the grid on which the solid body is built.Clay has three phases:

1. Fluid when it contains a lot of water
2. workable when it contains normal water
3. Solid when dried.

In the forming phase, the clay material is workable, and when the material is dried it is solid.There are several empirical tests if clay contains proper amount clay and if it is suitable material for building a structural element. It has been observed, however, that these tests have extremely large errors.For the exact determination of clay we use the device called the "hydrometer or densimeter " or Vougiouku method (Gasparatos 2011).

The earth to be examined is dried; rubbed and sieved to 2 mm. Weight 50g of soil were placed in a bowl with 40 ml of dispersion solution, which is removing agglomerating agents and demineralize water.After stiring this for 5 min and then place it on the graduated cylinder where water is added to the 1st roll of the cylinder (1130ml) along with the densimeter. After removing the densimeter from the cylinder, the mixture is mixed and set the zero time of the measurements.

As the coarse aggregate materials precipitate faster than the fine grain aggregate materials, densities are measured using a densimeter in a suitable solution to precipitate the sand first (measurement after 40 seconds) and then the silt (measurement after 2h). The clay remains suspended.
After the test, the results forthe material are ranked according to the percentages of the various components in a triangular imaging matrix.

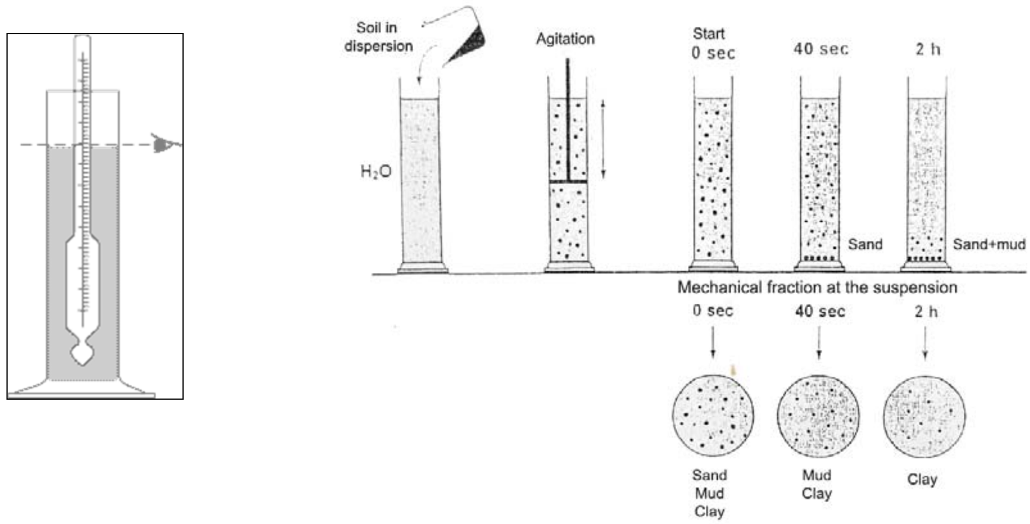


Figure 5.1: Determination of the mechanical composition of the soil by the Vougiouku method (source Gastaratos 2011)

If e.g. we have 45% clay, 20% slit and 35% sand, we would have the following diagram.

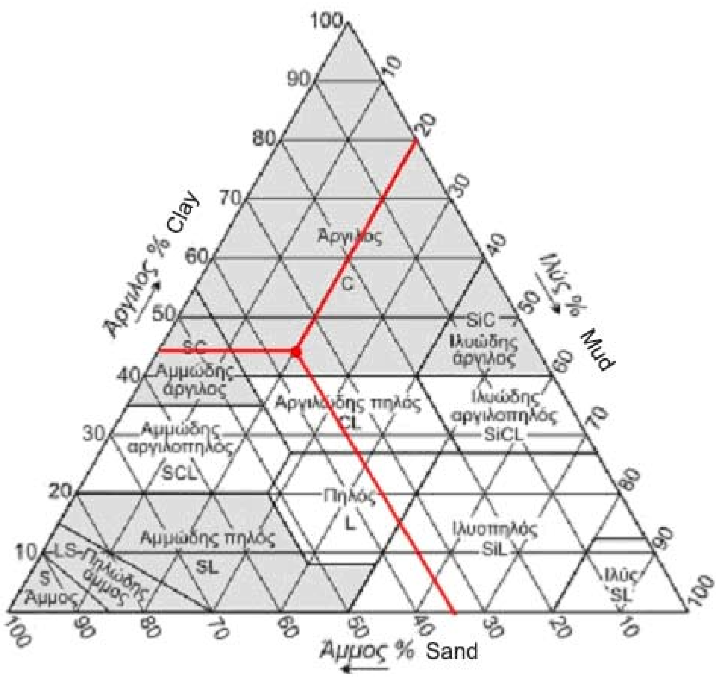


Figure 5.2: Triangular representational grid. The mortar is classified as " clay loam”

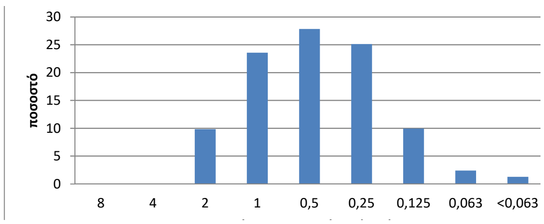
We know that in order to have a suitable mortar for earth’s construction it should contain ~15% to ~20% clay (Bey 2004). So in the soil of the test, we should add sand so as to reduce the percentage of clay in it.It is noted that the factor that plays a role in the mechanical behavior of the clay is the type of “clay” it contains but this is not described in the present essay.

5.3 The sand

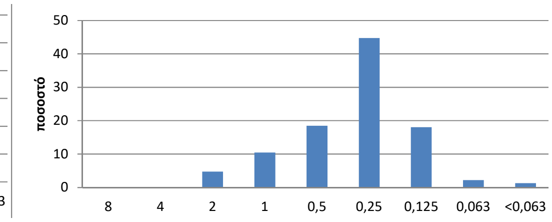
The sand we use in mortar must be free from salts and other undesirable impurities and be of good grading.The determination of its granulometric composition is necessary to determine the mechanical characteristics of the soil and its suitability for structural applications and is carried out according to DIN 4188.

So in the sieve used to siftthe sand [2, 1, 0.5, 0.25, 0.125, 0.062] when we want to make eg. a bonding mortar, there must be some relative restraint, meaning not holding all the sand in one or two sieves.

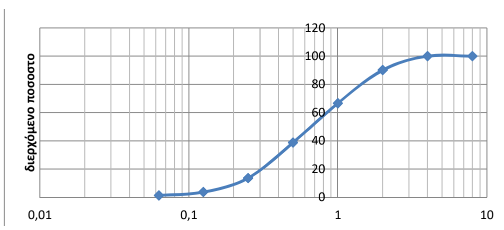
Then a good and a poor granulometric curve are presented.



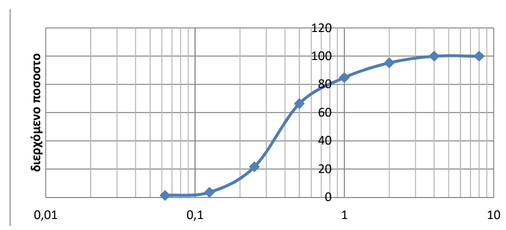
Distribution of the percentage of retained mass of aggregates/ sieve diameter (mm)



Distribution of the percentage of retained mass of aggregates/ sieve diameter (mm)



Sand with good grading/ coccimetic curve



Sand with poor grading/ coccimetic curve

Figure 5.3: Comparison of grain size of different kinds of sand

It is noted that for the formation of blocks and other structural elements it is possible that the grain of the largest aggregate may differ and gravel may be acceptable.

Figure 5.4: Granulometric analysis (photos by Ramin Antoniades)

5.4 Water

Water activates the clay of the soil and makes it workable. The hardness of the clay allows the material to be formed on surfaces, masses or molds.Depending on its use, the material must be tight (with little water) or more workable (with more water).When the clay is activated with water and becomes workable, it is agglomerated with other materials and consolidated with other pieces of clay.

It is noted, however, that adequate water is required because if more water than necessary is added on the earth, the mechanical strength of the material does not increase substantially, while the contractions occurring during drying are increased, resulting in cracks in the material.

5.5 The mixture of the materials

Depending on the shape of the component and the workability of the mixture required, various compositions are created.For the earth as building material, the soil is collected with as few organic as possible (roots etc.), preferably close to the structure.The soil must be sieved and have a grain diameter of less than 2 mm. Then the percentage of clay by the Vougiouku method must be found.
A soil suitable for structural use with satisfactory mechanical strengths contains clay between 15-20%. If for example, the result is of 25%. clay, then an indicative, like sand should be added to reduce the amount of clay.Surveys and experiments have shown that the amount of clay in the soil used in a coating should be between 5-12% to have small drying contractions and not cracked.

5.6 Determination of the appropriate percentage of clay in the mortar

Suppose we have sieved soil with a diameter of less than 4 mm and we characterize it as: x soil (clay + aggregate). In the examined soil x, a percentage of clay = 22.5% has been found which is too much for our material to be suitable, so we have to add aggregates (usually sand).
With y, we characterize the amount of sand we need to add to make the mortar appropriate.
The final mix (x + y) will apply:
0.225 • x => clay
0.775 • x + y => inert

Therefore, in order to achieve the required percentage of clay chosen to be 17.5% (average material suitability), we must:

$$\frac{0.225 \cdot x}{x + y} = 0.175 \quad (1)$$

So the amount of aggregates results from the relationship:

$$\frac{(0.775 \cdot x) + y}{x + y} = 0.825 \quad (2)$$

From the relations (1) and (2) it follows that x ≈ 3.5 y or y ≈ 0.3 x

This calculates the amount of additive aggregates (sand) required to add to the mortar so that it has a content of ≈ 17.5% in clay.

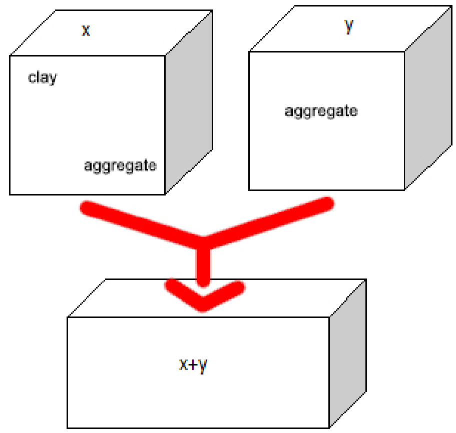


Figure 5.5: Mix of earth and aggregates

5.7 Finding "proper" water

For the determination of the proper water, mortar is prepared and is mixed in the mixer while water is gradually added there in about 15-20%. Mixing must be continued until the mortar has been homogenized and can be done by pressing or kneading.
To determine the normal water, the mortar is placed in the spreader bank where the frustum container is located with the hopper above.

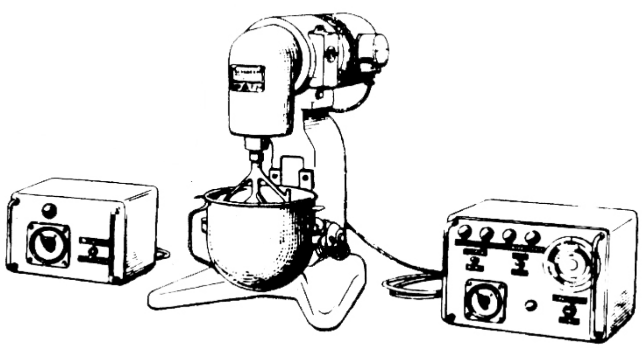


Figure 5.6: Mortar Mixer [Koroneos 2005]

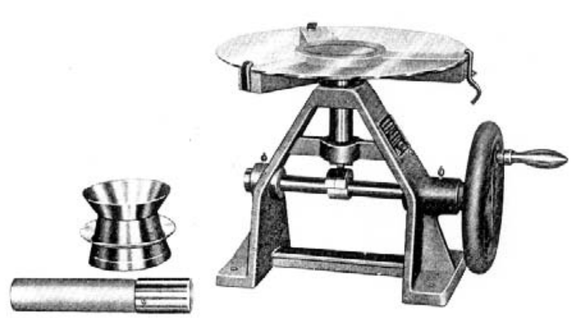


Figure 5.7: Distribution bank [Koroneos 2005]

It has been filled up to the middle with mortar from the mixer and tapped lightly with the wooden cutter 15 times, then filled up and beating another 15 times, so the hopper is removed and the surface of the mortar is flattened with metal rule.

Subsequently, the canister is removed and the lever is manually rotated 15 times, where upon 15 strokes are made in the spread table. The mortar is spread out and the average value of two vertical diameters α1 and α2 is the spreading measure α.

Figure 5.8: Testing the specimen in the spreading bank

That is: $a = \frac{\alpha_1 + \alpha_2}{2}$ cm

The amount of water is considered normal when it is between 13 <α <15 (Bey 2004).

5.8 Drying contractions and mechanical strengths

To examine the mechanical strengths of a material, test specimens are prepared, which are evaluated by appropriate laboratory devices at 28 days, 3 and 6 months.The test pieces must be 40 * 40 * 160 mm in size and they are called Feret's prisms.

Shaped molds with corresponding internal dimensions are used for the test. The molds are made of hard steel and are three-dimensional in order to make three samples simultaneously (Figure 6).The test specimens' samples maintain in the air.The determination of mechanical strength is done according to EN 1015 11: 1999.

For the determination of flexural strength, the prism specimen of the mortar (4x4x16 cm) is placed on the test device with its side facing the support rollers (to ensure good contact of the cylinders in the specimen) and its longitudinal axis being perpendicular to the supports.

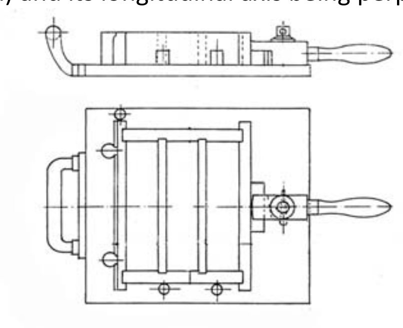


Figure 5.9: Mold prisms 40 * 40 * 160 mm (Feret) [Koroneos 2005]

Figure 5.10: Laboratory matrices for various tests

The specimen is loaded vertically by applying the loading roller to the opposite side of the prism.For the determination of compressive strength, the two broken parts of the bended specimens are used. They are placed along their length in the center of the plates of the compression device in such a way that the edge of the prism protrudes about 10 mm from the edges of the plates.

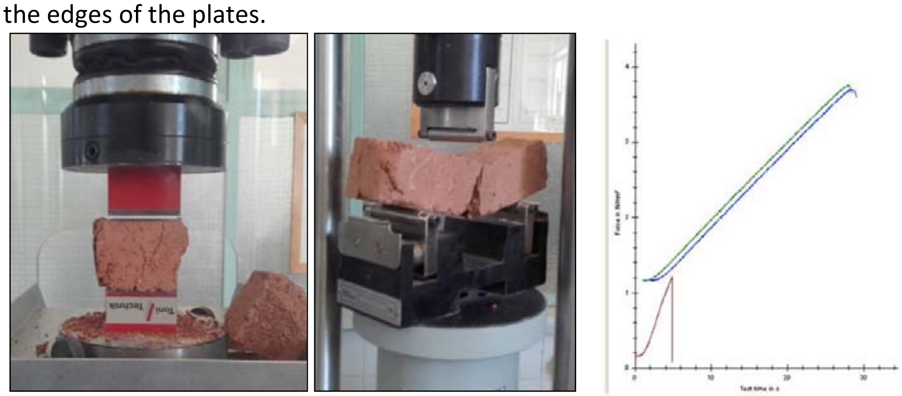


Figure 5.11: Experimental devices and results of compressive strength and bending of three points of Earth mortar

5.9 How the material's characteristics change

In the preparation phase of the mortar with earth, the material is in shaping state and also it is flattened. During the drying of the material, the material gradually solidifies and acquires mechanical strength. A characteristic marker which varies in the solidification phase of the material is the dynamic modulus of elasticity of the material.

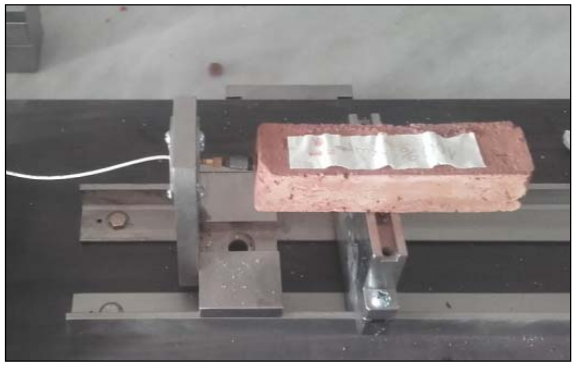
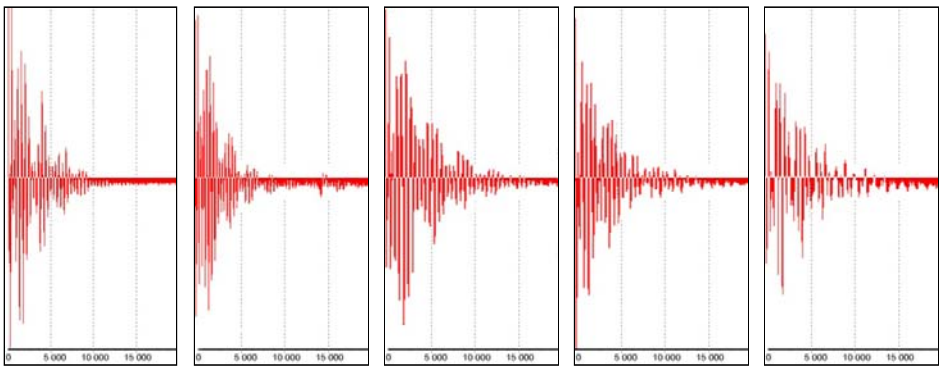


Figure 5.12: Experimental arrangement of the dynamic modulus E



1^nE: 2.2 GPa2^nE: 3.1 GPa 3^nE: 3.3 GPa4^nE: 3.3 Gpa 5^nE: 3.6 GPa

Figure 5.13: Distribution of dynamic modulus of elasticity earth specimen E during the drying for 5 weeks

The determination of the potential modulus of elasticity is a non-destructive method and the relative diagrams show its change to a standard earth sample in its drying phase (5 weeks) with content 17.5% clay.

To interpret the changes in a soil it was chosen to test a soil rich in clay (~ 40%) by adding normal water and with more than normal water, by adding various types of aggregates and natural additives such as whipped egg (meringue), water with flour and rice water cooked for a long time.

It has been observed that the effects of mechanical strength of geogrid depend on the humidity of the environment. Thus, there may be subtle changes (5-10%) between tests of a dry period of summer and a wet winter period (lower strength).Indicative results of the change in volume and mechanical strength are shown in the following diagrams.

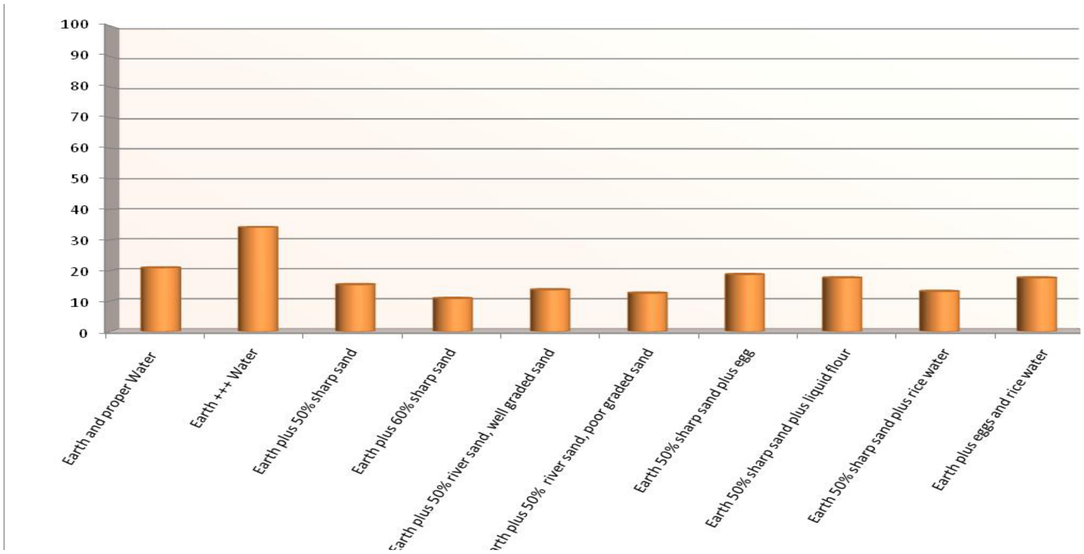


Figure 5.14: Volume change of mortar with earth land ΔV / V (%)

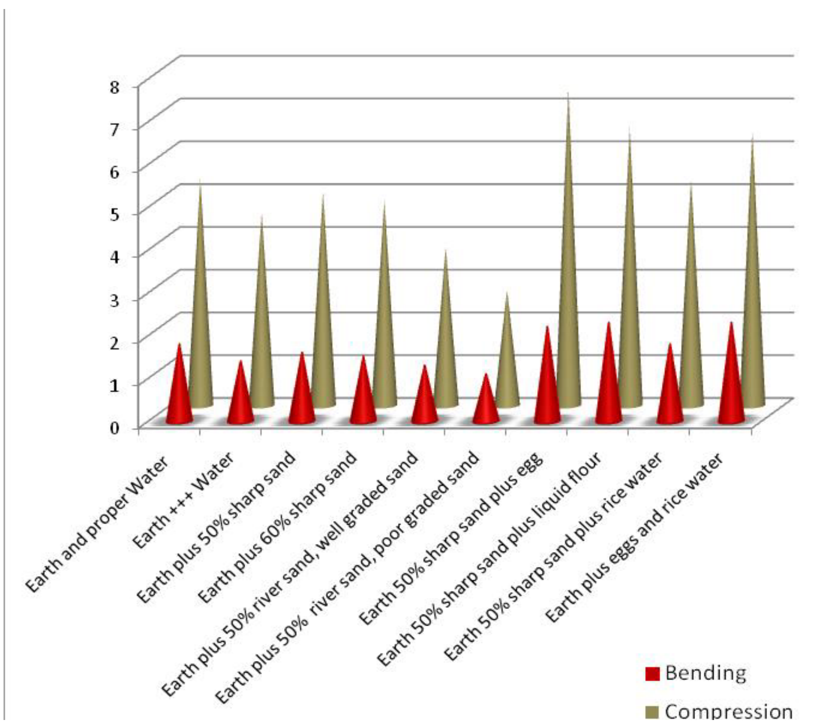


Figure 5.15: Compressive strength and bending of three-point mortar with earth in MPa

6 Applications of Earth as building material in Greek Architecture

Some of the world's most magnificent structures were made of earth and water, from New Mexico's pueblos to the great Djinguereber mosque in Timbuktu (1327).In Greece and especially in areas like Thessaly, Prespes, Athens and Crete were constructed several buildings using earth as basic building material; sometimes in combination with local stones and wood as bearing system.

Figure 6.1: A building in Apokoronas Crete

Figure 6.2: In the way to European Sustainability Academy in Apokoronas Crete

7 The mud house in Trikala

Figure 7.1: The mud house in Trikala, owner : Konstantinos Katavoutas

7.1 The adobe houses of Thessaly

There is a massive tradition of adobe building in the plains of Thessaly. Until the 1920's Thessaly was a semi feudal society with the land owners living in stone haciendas and the peasants in adobe houses or, worse, in wooden huts. Many of them have endured earthquakes, floods, decades of disrepair and stand until now.

Figure 7.2: Constructions with earth. Traditional adobe houses in Trikala

So when the decision to experiment with adobe in Trikala was not out of context. Was it out time? Is it adobe building an outdated way of building and all the new mud houses that we build today postmodern sentimental attempts to resurrect an obsolete technique? Time will tell, but our goal was to examine if it is feasible to construct a new house from natural materials without compromising the safety, comfort and financial standard of modern housing.

7.2 Design and building permission

The plan of the building is "Γ" shape, one of the basic local types, which also permits the expansion of the house, if the family needs increase. We examined also some more modern ones but we stayed at the most safe one; one step each time.

The building has a wooden "post and beam" frame which permits the roof to work independently from the adobe walls, at least in theory. In Greece due to the strict anti-earthquake code it is not possible to construct a house with load bearing adobe walls. Since the house was relatively small we were exempted from the new energy - saving codes, so we were not forced to add external insulation at the adobe walls.

7.3 The construction of adobe bricks

The excavation soil was not adequate so we had to buy soil from a nearby site. The bricks were made from three local builders. They were not of course specialised in adobe but in floors, but anyway they had a basic building experience.

The mix was a receipt of mine, after examining the empirical tests. The process was basically handmade, but we used a mechanical mixer, which made our life simplier. The soil mix was been put in a 8-brick mould and it was left for 3 days for drying. Afterwards it was turned upside down and left for two additional days and then the bricks were layered in wooden pallets. After 20 days in total they were ready for building. The three member team was able to produce 500 bricks a day and it have to provide 1000 square metres for the drying of the bricks. Me, my family and our neighbours made the auxiliary tasks (cutting of the straw, turning and layering of the bricks etc).


Figure 7.3: The building process

7.4 Wooden frame

It was one of the most interesting phases of the construction. In three days we had a beautiful post and beam wooden frame and a wooden insulated roof with ceramic rood tiles.

Figure 7.4: Wooden frame details

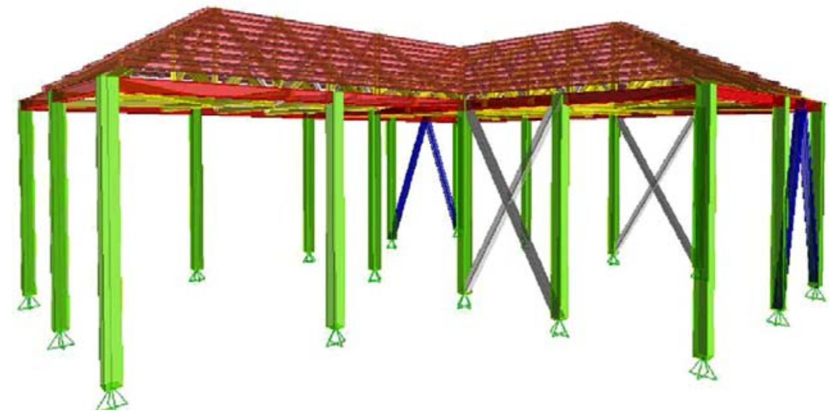


Figure 7.5: Wooden Load bearing system

7.5 Wall building

It was extremely difficult to find builders to build and to find a mutually accepted way of paying them, because it was not easy to predict the schedule. Finally we find a very skillful one which mad very nice job. I have to add that we live 320 km away from the site and all the building was made in our summer vacation and in extended weekends.

Figure 7.6: The mud house in Trikala, construction phase

The mortar mix was similar to the adobe mix with a bit of sand more and we put two wooedn zones of horizontal reinforcement. The external walls have depth of 50 cm and the internal ones 30 cm.

7.6 Plastering, paints etc

Figure 7.7: Plastering the adobe house

The plastering was made without using any cement because we wanted the natural masonry to have the ability to breathe and to let any trapped moisture to escape. We used an old recipe of an pensioned builder who used in the centre of Athens until the mid 70s and it was consisted of lime, sand and marble dust. The paints was also natural ones who let the moisture to circulate freely. In the bath I tried to experiment with tadelakt (with good results after 5 years of living) and my father felt like a self taught carpenter and made the wooden cupboard, a closet and additionally a bed and a table with wood that was not used for the wooden frame. We installed a wooden stove for heating although we examined the solution of a pellet one, for financial and simplicity reasons.

Figure 7.8: The mud house in Trikala

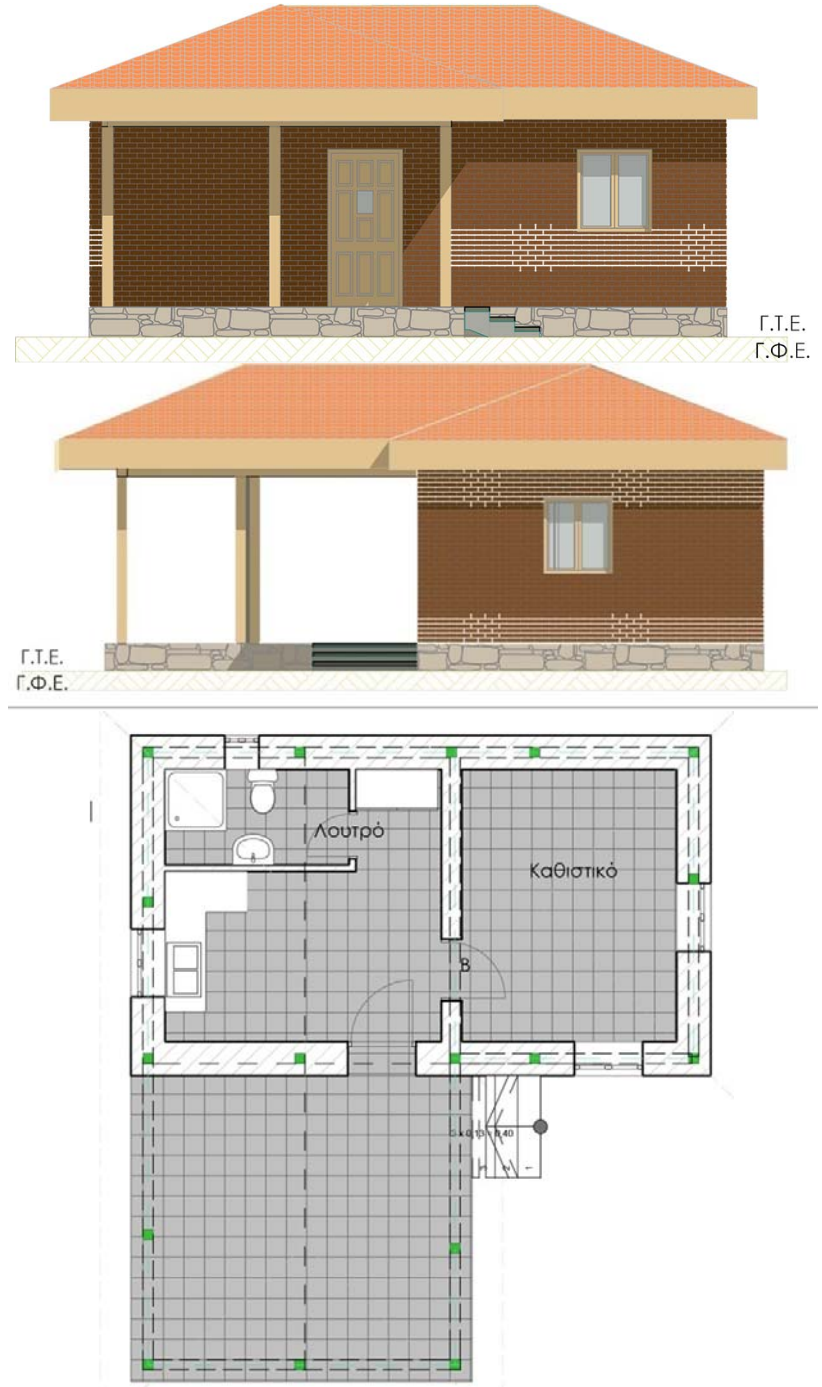


Figure 7.9: Front view, side views and the plan of the mud house

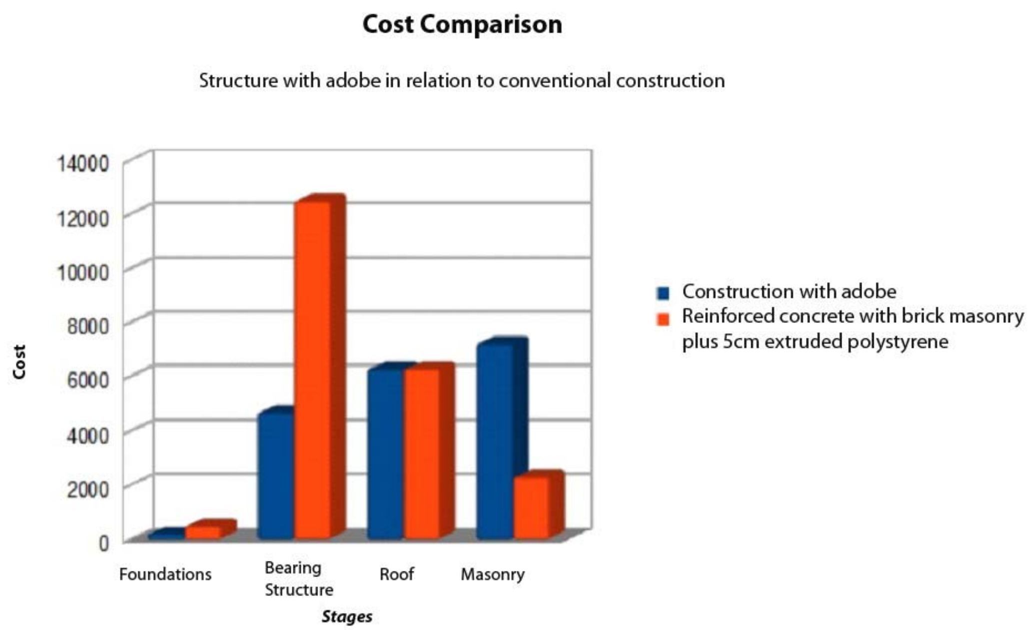


Figure 7.10: Cost comparison of adobe house and reinforced concrete with brick masonry

Comparing the cost of our building with that of a conventional building we conclude that the reduction of the cost was less than what we hoped for. Actually the adobe bricks costed much more than if we had used bricks (with core insulation included). The reason for that is that adobe building is labour intensive and wages in Greece are, fortunately and for the time being, at acceptable levels. Additionally we wanted to be on the safe side so we overestimated the amount of the bricks, which was adequate for a house much bigger. And last but not least the drying process was made in an uneven surface, so the produced bricks had not a flawless shape, which made difficult the building process.

This was compensated by the massive reduction of the cost of the bearing structure. In a one storey house of that size concrete may be an overkill and we were able to save money with a light and fast to construct, post and beam timber frame.

7.7 Conclusions by the construction of the mud house in Trikala

The construction was a beautiful though time-consuming and stressful process. A large part of the problems was due to the inexperience and I guess if a similar project it was to be repeated some difficulties would be omitted. But we have to admit that the size of the project was small and I am not sure if I would advice a land owner to build a medium size house as a primary residency. The cost was a bit lower from a conventional one of the same size. The adobe masonry resulted much more expensive than a brick one, because it is a labour intensive process and for the time being, thankfully, the builder wage is not extremely low. That fact was mitigated from the extremely cheap wooden frame comparing with a concrete one.

Another problem that a possible designer would face is that the energy saving code treats the adobe with a, counterintuitively, very strict way and he would add external insulation, even in regions with a mild climate, Thessaly is not one of them with its extreme climate.

So if we, the technical world, want to use mud as a building material, even in a marginal way, we should find responses to these matters: cost and energysaving.

The cost, if we talk about industrialised western societies is a matter of scale. Small manufacturers should build adobe or compressed earth bricks off-site, so the builder and the land owner would find them ready to use.
For the energy saving I, and many more, believe that the adobe wall as a system and not as a building unit is behaving better that the codes say, but we can not prove it. So research should be made in the energy behaviour of abode walls and we also expect clever solution on how we should use adobe walls in conjunction with additional insulation.

8 Vafes House in Apokoronas of Crete

8.1 Description of the project

Figure 8.1: Front view

Residence in traditional settlement, of 90m², built in 2011, from Southern Architects, Mousourakis Apostolos.
The design of this new residence in the traditional settlement of Vafes Apokoronas in Crete, attemped on one hand to satisfy the modern criteria of sustainability and on the other hand to integrate organically into the existing residential area. The building typologically follows the traditional architecture of the settlement leaning along one side on an existing building, and communicates with the other two existing buildings creating an inner courtyard within the complex to which it belongs. The main two-storey tile-roofed building has been constructed using the technique of a wooden carrier with a lightweight mixture of straw and clay.
The construction of the lightweight straw and clay was made by unskilled laborers after being trained by the supervising engineer of the project and with the help of a secondary wooden frame. External lime plaster and internal mud plaster complete the final surfaces of the building, which are finished with lime paints in earth colours. The two small ground-floor sections of the building which are slightly underground and house the kitchen and bathroom, have been constructed with masonry-bearing brickwork made of heat-insulating bricks and their roof is accessible from the upper floor.

8.2 Main techniques used for construction of Vafes House in Apokoronas of Crete

Figure 8.2 Wooden load bearing structure

Figure 8.3 Lightclay

Figure 8.4 Interior earthen plasters

Figure 8.5 Exterior limeplasters (photos by E.Frangedaki)

Figure 8.6 Interior, detail of the 1st floor

Figure 8.7 Interior in the ground floor

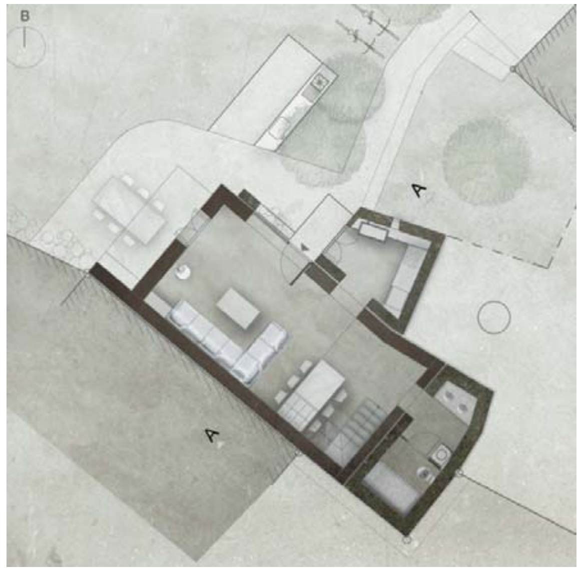


Figure 8.8 Plan of the ground floor

Figure 8.9 Plan of the first floor

9 Conclusions

There are many tests that can be done to control an earth mortar, but research into one material can be done infinitely. In the present work, some formal, laboratory and reliable tests have been formulated to evaluate this material for its use in earth-made structures.

Finally, if architectural thought decides to revise this material into its constructions, the control and standardization of this material is ambiguous, since it has been found that empirical methods involve large errors to be considered as sufficient characteristics for its accreditation.

Earth is now now up-to-date as its ecological and aesthetic benefits attract the attention of an increasing number of contemporary architects and eco-builders. Industrial sectors devoted to earthen buildings are currently emerging as this sustainable material wins over.

Furthermore, earth has good acoustic properties, high thermal mass, fire resistance and durability and other properties that can create a modern usage for a primary material.

Each country has its own experience and culture, heritage and motivations for the use of earth in construction. In some countries earth is the only available material, and in some other this technique has been used in the past but now it's forgotten. In the face of a climate change, people must be more responsible for creating environmentally sustainable building.

The advantages of building with earth has to do with:

- Economy
- Sustainability
- Environmental advantage

The earth is a common good, so care must be taken to ensure that non-renewable earth materials will be over-extracted. Ecological balance needs to be maintained while efficiently utilizing its resources. Also, it must be taking special care of the material so it won't be shipped in from long distance areas. Earth products must be locally produced or quarried.

Nowadays, mechanical extraction is the more likely method, but assuming the earth is sourced fairly locally to the site, it is still a very low-energy input form for construction.

The transportation of large amounts of earth is potentially an energy-intensive and polluting process. However, the distances involved are rarely that great and the overall energy cost is certainly much lower than the conventional alternatives of cement, sand and aggregates.

All earth buildings tend to have a high 'thermal mass', as earth is a dense material, particularly when compressed. This means that they can absorb and store solar energy, and re-release it in the form of heat when the building cools down, usually in the evening. The earth buildings have the effect of modifying temperature extremes internally, and are more comfortable and energy efficient than many conventionally built houses. High thermal mass is an essential component of passive design. Earth is also highly hygroscopic and so helps to regulate humidity. When installed to a sufficient thickness, earth is a reasonably good insulator, and on demolition, it will simply revert to earth.

10 Bibliography

1. Bei G., Clay masonry: experimental investigation of mechanical and physical properties of structural units and walls of compressed Earth bricks," Τοιχοποιία από πηλό: πειραματική διερεύνηση μηχανικών και φυσικών χαρακτηριστικών δομικών μονάδων και τοίχων από Συμπιεσμένες Ωμόπλινθους", Doctoral thesis, Aristotle University of Thessaloniki, Thessaloniki 2004.
2. Bjørn Berge, The Ecology Of Building Materials, Second edition, Translated by Chris Butters and Filip Henley, Architectural Press is an imprint of Elsevier, First edition 2000 Second edition 2009
3. Development, research, promotion and dissemination of ecological architecture, "Ανέλιξη, έρευνα προώθηση και διάδοση οικολογικής αρχιτεκτονικής", http://www.anelixi.org/, (Retrieved: September30, 2015).
4. Edwards B. & D. Turrent, Sustainable Housing, Spon, London 2000.
5. Fathy H., Architecture for the Poor: An Experiment in Rural Egypt, University of Chicago Press, 2010.
6. Gassaratos D., St. Karavasilis and F. Giannakopoulou, Exercises of General Soil Science, "Ασκήσεις Γενικής Εδαφολογίας", Agricultural University of Athens, Department of Natural Resources Development and Agricultural Engineering, Athens 2011.
7. *http://earth.sustainablesources.com/*
8. http://vinopedia.hr/ (πρόσβαση 3 Οκτωβρίου 2015)
9. http://xtizontasmexoma.blogspot.com/2010/10/blog-post.html
10. https://terrabrasil2010.wordpress.com/
11. https://www.designboom.com/architecture/earth-a-building-material-of-the-future/
12. https://www.dezeen.com/2017/12/01/movie-waf-world-building-of-year-winner-earthquake-resistant-video/ κτίριο από πλιθιά.
13. https://www.eurosustainability.org/
14. Khalili N., Ceramic Houses and Earth Architecture: How to Build Your Own, Chelsea Green Publishing Co, USA, 1996.
15. Khalili N., Emergency Sandbag Shelter and Eco-Village, CalEarth Press, USA, 2008
16. Koronaios Em., G. Poulakos, Technical Materials, "Τεχνικά Υλικά", volume 3, ed. NTUA, Athens 2005.
17. Minke G., Building with Earth, Birkhauser, Publishers for Architecture, Basel, 2006.
18. Minke G., Building with Earth: Design and Technology of a Sustainable Architecture, Walter de Gruyter, Appendices

19. Minke G., Earth construction handbook: the building material earth in modern architecture, WIT Press, Southhampton [UK], 2000.

20. Morel JC, Mesbah A, Oggero M, Walker P (2001) Building houses with local materials: means to drastically reduce the environmental impact of construction. Build Environ 10(36):1119–1126

21. Sargentis G.-Fivos and N. Symeonidis, Earth as a Material, "Η Γη ως Υλικό", eco-dome (urban non-profit organization for sustainable architecture), Athens 2010.

22. Sargentis G.-Fivos, Mechanical-Environmental aspects and applications of earth as building material, SADAS-PEA: 13th Weekly Workshop - Seminar "NATURAL STRUCTURE AND ALTERNATIVE RESTORATION", Stamou Stourna Hostel, Ali Meria Volos, 26 May to 1 June 2018.

23. Sargentis, G.-F., V. C. Kapsalis and N. Symeonidis, Earth building. models, technical aspects, tests and environmental evaluation, 11th International Conference on Environmental Science and Technology, Crete, Department of Environmental Studies, University of the Aegean, 2009.

24. Walker P, Stace T (1999) Bond characteristics of earth block. J Mater Civil Eng 30:249–256

11 Appendix. Construction techniques

ADOBE·WATTLE & DAUB·RAMMED EARTH·COB·EATH BAGS

CONSTRUCTION WITH EARTH

SCENARIO

PETRAKIS PETROS
SPANIOLOS ISIDOROS
HAVAKIS KIRIAKOS

ILLUSTRATION

MIHALENAS VASILIS

TRANSLATION and REVISION:

EVANGELIA FRANGEDAKI

G.-FIVOS SARGENTIS


TAKI, HOW MANY METERS DO WE DIG?
WE HAVE ALREADY DUG THIRTY CENTIMETRERES,
THE EARTH AT THIS SITE IS RICH AT CLAY.
I BRING THE STONES FOR THE SUBSTRUCTURE
YOU PREPARE THE MUD
EXCELLENT MITSOS, BRING ME THE STRAW.
THE MUD IS READY FOR USE.
I WILL MAKE THE ADOBE USING A MOLD.
I NEED YOU FOR A WHILE.
HELP! ME PLEASE! BING ME ANOTHER MOLD.
YES, I'M COMING.
I 'M GOING TO FINISH THE FOUNDATION FIRST.
THE NEXT DAY.
GIVE ME SOME MORE BRICKS PLEASE.
AND THEN MAKE A STRING GUIDE.
IT'S FINE!
LAID ADOBE BRICKS WITH MUD MORTAR AND THAT'S ALL!


BRING ME SOME MORE BOARDS. WE HAVE TO MAKE TREE MORE TIMBER FRAMES.
ONE MORE ADJUSTMENT AND I'M DONE WITH IT.
I WILL NAIL DOWN THE BOARDS TO THE FRAMES.
IT WILL TAKE SOME TIME.
WHEN THE WATTLE PANELS ARE CONSTRUCTED EVERY LINE OF WITHIES MUST BE PRESSED DOWN FIRMLY.
THE DAUB CAN BE APPLIED NOW AND THE WALL IS READY.
WE DID IT!


EMPTY THE STONES NEXT TO THE EXCAVATION AND I 'LL BRING SOME MORE
I SELECT THE STONES SO THEY FIT CLOSELY TOGETHER
I DIG HERE WHERE THE SOIL CONTAINS A LOT OF CLAY, AS FIVOS TOLD US
I OPEN A HOLE AROUND 30 CM.
ISIDORE, BRING SOME WATER TO ADD TO THE EARTH MORTAR.
WE DON'T NEED TO ADD MORE CEMENT
OK I HOLD IT FIRMLY AND YOU KEEP HAMMER NAILS INTO THE BOARD.
APPLY THE MORTAR SLOWLY SO I CAN GRADUALLY SPREAD IT
OK
TROWEL THE MORTAR CAREFULLY TO ADHERE TO THE STONES.
HEY WHIPPERS, I WET THE EARTH SO THE CLAY SOIL WILL BE MORE ADHESIVE
BRING IT WITH NO RUSH
OK GUYS I SPREAD THE CLAY
IDIDORE, BRING ME THE TROWEL TO APPLY THE MORTAR IN THE MOLD. YOU KYRIAKO, BRING THE MANUAL TAMPER.
AFTER SOME REPETITIONS WITH THE TAMPER OVER THE ENTIRE SURFACE OF THE LAYER; THE WALL IS READY.

HE MADE ME CARRY ALL THE MATERIALS AGAIN
LET IT BE, HE WILL PREPARE THE MORTAR IN HIS OWN
WE ARE SO CLOSE TO FINISH THE DIGGING.
GOOD;I 'M GONNA HELP YOU WITH THE FOUNDATION.
THE STRAW IS ENOUGH
DON'T ADD ANY MORE
IS IT PLACED OK, KIRIAKOS?
YES, THE SIDES ARE LEVELED.
TO FORM THE DOORWAY WITH A DOOR FRAME WILL BE DIFFICULT
YES INDEED, IT WILL TAKE SOME TIME
WE'VE ALMOST DONE IT!
YES!


COME HERE TO HELP ME!
BUT I CARRIED THE TOOLS.
DIG OUT A TRENCH AROUND 30CM BELOW, LIKE THIS!
YES!
YOU KEEP TAMPER TO FLAT THE LAYER OF SOIL
HOW MUCH SOIL DO WE FILL EVERY BAG?
FILL BAGS APPROXIMATELY 90% FULL!
WATCH THE ADDED GUIDES & STRINGLINES FOR BETTER CONSTRUCTION OF THE DOME.
OK!
DID YOU FINISH THE CUT OFF OF THE BAG EXCESS MATERIAL?
NOT YET!
GOOD, WE ALMOST FINISHED!
LET'S START TO ROUGHCAST THE WALL.
WE FINISH AFTER WE TROWEL THE PLASTER ONTO THE WALL.