Escola de Camins
Escola Tècnica Superior d'Enginyeria de Camins, Canals i Ports
UPC BARCELONATECH

DISSERTATION PROJECT

Collaboration of Escola Técnica Superior d'Enginyers de Camins Canals i Ports de Barcelona with Warsaw University of Technology

RAMMED EARTH AS A CONSTRUCTION BUILDING MATERIAL

Author: Alberto Gaudó Labarta

Tutor in WUT: Piotr Leon Narloch

Tutor in ETSECCPB: Marilda Barra Bizzinotto

Degree: Civil Engineering

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Acknowledgements

The author would like to render thanks to all the people that made possible the realisation of this project.

First of all the author would like to acknowledge pf. Piotr Leon Narloch from the Warsaw University of Technology for helping him with the project by providing information, ideas and knowledge of earthen structures, particularly about rammed earth with entire disposal to help and to meet when necessary because of his particular difficult situation with deadlines.

It is necessary to mention Stephen Dobson, as director for, Ramtec Pty Ltd. for providing first-hand information on how its company works regarding the subject on rammed earth in a very clear and fast way.

The author would also like to thank his university colleagues who helped him whenever he had a doubt regarding to the project without doubt.

To all the people who made this project possible, in a direct or indirect way, the author wants to thank you.

Abstract

This project main objective is to expose the pros and cons of rammed earth as a building material.

Firstly, the advantages of earth building will be explained, different methods of construction with soil will be exposed as an illustration, some of which are popularly known and finally the author will try to argue why rammed earth is the chosen method for building.

Secondly, the technique of rammed earth will be explained with detail. Properties and composition of this material will be developed, which characteristics have to be considered and some values of compaction, strength and durability will be shown.

In the third place, this document will show some experiments performed in order to understand better how this material works and some of its limitations. In order to avoid this limitations, some new techniques (additives) will be shown in order to improve the material, and it will be tried to determine which one is the best one among them.

Finally, construction about the world will be exposed and analysed, what are the reasons that make this material suitable for building in some areas and not in others, depending not only on weather but on social impact.

Introduction

Traditional unfired earth building materials were the most important constructions in past societies and it is estimated that today one third of world's population live in this type of constructions. This conventional material has proved to be good for building due to its longevity (some buildings remain after hundreds of years) and his other good qualities such as thermal insulation and low environmental impact.

Ironically rammed earth constructions nowadays are seen as "non-conventional" or "alternative" construction methods when are one of the oldest techniques in our history and in western countries could even be considered a poor material or structure in which only people without resources would live. Far away from reality rammed earth has proved to have excellent qualities for building. This ancient technique combined with modern methods and improvements could bring significant contributions to building world.

Standardisation of this constructions have already begun in world's zones with more use of it such as New Zealand and Australia and in several countries this process is under development, just like Spain. The knowledge of rammed earth we have is not poor, we do have lots of experience and thousands of ancient constructions which are proof of that. The problem with standardization of rammed earth is that the soil used in each construction is the one available on the surroundings and this soil and his characteristics depend on the country, more precisely on the zone, that is why is difficult to standard it in one only code.

In this work it will be exposed what is rammed earth, his components, characteristics and how can we improve it for example adding cement. Also will write about some examples around the world and legislature around the world with its respective laboratory tests.

History

Earth construction techniques have been known for over 9000 years. Mud brick houses dating from 8000 to 6000 BC have been discovered in Russian Turkestan. Rammed earth foundations dating from 5000 BC have been discovered in Assyria. Earth was used in all ancient cultures, not only for homes but for religious buildings as well. The 4000-year-old Great Wall of China was originally built solely of rammed earth; only a later covering of stones and bricks gave it the appearance of a stone wall. The core of the Sun Pyramid in Teotihuacan, Mexico, built between 300 and 900 AD, consists of approximately 2 million tons of rammed earth [1].

Bronze Age discoveries have established that in Germany earth was used as an infill in timber-framed houses or to seal walls made of tree trunks. The oldest example of mud brick walls in northern Europe, found in the Heuneburg Fort near Lake Constance, Germany dates back to the 6th century BC. We know from the ancient texts that there were rammed earth forts in Spain by the end of the year 100 BC. In Mexico, Central America and South America, adobe buildings are known in nearly all pre-Columbian cultures. The rammed earth technique was also known in many areas, while the Spanish conquerors brought it to others. In Africa, nearly all early mosques are built from earth.

In the Medieval period (13th to 17th centuries), earth was used throughout Central Europe as infill in timber-framed buildings, as well as to cover straw roofs to make them fire-resistant. In France, the rammed earth technique, called *terre pisé*, was widespread from the 15th to the 19th centuries. Near the city of Lyon, there are several buildings that are more than 300 years old and are still inhabited. The technique came to be known all over Germany and in neighbouring countries. In Germany, the oldest inhabited house with rammed earth walls dates from 1795. Its owner, the director of the fire department, claimed that fire-resistant houses could be built more economically using this technique, as opposed to the usual timber frame houses with earth infill. The tallest house with solid earth walls in Europe is at Weilburg, Germany. Completed in 1828, it still stands. All ceilings and the entire roof structure rest on the solid rammed earth walls that are 75 cm thick at the bottom and 40 cm thick at the top floor (the compressive force at the bottom of the walls reaches 7.5 $^{kg}/_{cm^2}$) [1].

In the pictures below we can see: the Sun Pyramid in Teotihuacan (figure 1), one of the biggest structures made with rammed earth, second (figure 2), the tallest house with solid earth walls in Europe, at Weilburg (Germany) and the third is a segment of the Great Wall of China in which we can see how is formed with rammed earth (figure 3).

Figure 1: The Sun Pyramid if Teotihuacan. Source http://www.learnnc.org/lp/multimedia/5514

Figure 2: Five floor house at Weilburg. Source
http://www.earthbagbuild.com/brief_history.htm

Figure 3: Section of the great wall of china made with rammed earth. Source
http://blog.builddirect.com/green-building-rammed-earth-homes/

Basics of earth as a building material

Earth when used as a building material is often given different names: loam is a mixture of clay, silt, sand and sometimes larger aggregates such as gravel or stones. Loam has three main disadvantages compared with other industrialised building materials:

Loam is not a standardised building material, because depending on the site where the loam is dug out, it will be composed of differing amounts and types of clay, silt, sand and aggregates. Its characteristics, therefore may differ from site to site, and the preparation of the correct mix for an specific application may also differ. In order to judge its characteristics and alter these, when necessary, by applying additives, one needs to know the specific composition of the loam involved.

Loam mixtures shrink when drying due to evaporation of the water used to prepare the mixture (moisture is required to activate its binding strength and to achieve workability), shrinks cracks will occur. The linear shrinkage ratio is usually between 3% and 12% with wet mixtures (such as those used for mortar and mud bricks), and between 0.4% and 2% with drier mixtures (used for rammed earth, compressed soil blocks). Shrinkage can be minimised by reducing the clay and the water content, by optimising the grain size distribution, and by using additives.

Loam is not water-resistant. Loam must be sheltered against rain and frost, especially in its wet state. Earth walls can be protected by roof overhangs, damp-proof courses, appropriate surface coatings, etc.

On the other hand, loam has many advantages compared to common industrial building materials:

Loam balances air humidity. Loam is able to absorb and desorb humidity faster and to greater extent than any other building material, enabling it to balance indoor climate. Experiments at the Forschungslabor für Experimentelles Bauen (Building Research Laboratory, on BRL) at the University of Kassel, Germany, demonstrated than when the relative humidity in a room was raised suddenly from 50% to 80%, unbaked bricks were able, in a two-day period to absorb 30 times more humidity than baked bricks. Even when standing in a climatic chamber at 95% humidity for six months, adobes do not become wet or lose their stability; nor do they exceed their equilibrium moisture content, which is about 5% to 7% by weight [1]. (The maximum humidity a dry material can absorb is called its "equilibrium moisture content").

Measurements taken in a newly built house in Germany, all those interior and exterior walls are from earth, over a period of eight years, showed that the relative humidity in this house was nearly constant throughout the year. It fluctuated by only 5% to 10%, thereby producing healthy living condition with reduced humidity in summer and elevated humidity in winter [1].

Like all heavy materials, loam stores heat. As a result in climatic zones with high diurnal temperature differences, or where it becomes necessary to store solar heat gain by passive means, loam can balance indoor climate.

Loam saves energy and reduces environmental pollution. The preparation, transport and handing of loam on site requires only 1% of the energy needed for the production, transport and handling of baked bricks or reinforced concrete. Loam, then, produces virtually no environmental pollution.

Loam is always reusable. Unbaked loam can be recycled an indefinite number of times over an extremely long period. Old dry loam can be reused after soaking in water, so loam never becomes a waste material that harms the environment.

Loam saves material and transportation costs. Clayey soil is often found on site, so that the soil excavated for foundations can then be used for earth construction. If the soil contains too little clay, then clayey soil must be added, whereas if too much clay is present, sand is added.

The use of excavated soil means greatly reduced costs in comparison with other building materials. Even if this soil is transported from other construction sites, it is usually much cheaper than industrial building materials.

Loam is ideal for do-it-yourself construction. Provided the building process is supervised by an experienced worker, earth construction techniques can usually be executed by non-professionals. Since the processes involved are labour-intensive and require only inexpensive tools and machines, they are ideal for do-it-yourself building.

Loam preserves timber and other organic materials. Owing to its low equilibrium moisture content of 0.4% to 6% by weight and its high capillarity, loam conserves the timber elements that remain in contact with it by keeping them dry. Normally, fungi or insects will not damage such wood, since insects need a minimum of 14% to 18% humidity [1] to maintain life, and fungi more than 20%. Similarly, loam can preserve small quantities of straw that are mixed into it.

However, if lightweight straw loam with a density of less than 500 to 600 ${}^{kg}/_{m^3}$ is used, then

the loam may lose its preservative capacity due to the high capillarity of the straw when used in such high proportions. In such cases, the straw may rot when remaining wet over long periods.

Loam absorbs pollutants. It is often maintained that earth walls help to clean polluted indoor air, but this has yet to be proven scientifically. It is a fact that earth walls can absorb pollutants dissolved in water. For instance, a demonstration plant exists in Ruhleben, Berlin, which uses clayey soil to remove phosphates from 600 m^3 of sewage daily [1]. The phosphates are bound by the clay minerals and extracted from the sewage. the advantage of this procedure is that since no foreign substances remain in the water, the phosphates are converted into calcium phosphate for reuse as a fertiliser.

Benefits of earth building on indoor climate

In moderate and cold climates people spend huge amount of their time in enclosed spaces so the conditions of indoor climate are vital for comfort and well-being. Comfort depends on temperature, humidity, radiation and movement and renewability of the air for pollutants.

For people inside the room the temperature is a factor that is immediately acknowledged and recognise if it's too high or too low whereas this doesn't happen with humidity. People do not realise if it is high or low and it has significant relevance in health of inhabitants inside the room. In this field, earth has the capacity of balance indoor humidity like no other building material.

Research has shown that a relative humidity of less than 40% over a long period may dry out the mucous membrane, which can decrease resistance to colds and related diseases [1]. This is so because normally the mucous membrane of the epithelial tissue within the trachea absorbs dust, bacteria, viruses, etc. and returns them to the mouth. If this absorption is disturbed by drying, then foreign bodies can reach the lungs and may cause health problems. A relative humidity over 70% has many positive consequences: it reduces the fine dust content of the air, activates the protection mechanisms of the skin against microbes, reduces the life of many bacteria and viruses, and reduces odour and static charge on the surfaces of objects in the room.

A relative humidity of more than 70% is normally experienced as unpleasant, probably because of the reduction of oxygen intake by the blood in warm-humid conditions. Increasing rheumatic pains are observed in cold humid air. Fungus formation increases significantly in closed rooms when the humidity rises above 70% or 80%. Fungus spores in large quantities can lead to various kinds of pain and allergies. From these considerations, we can conclude that the humidity content in a room should be a minimum of 40%, but no more than 70%.

The impact of air exchange on air humidity

In moderate and cold climates, when the outside temperatures are much lower than inside temperatures, the greater degree of fresh air exchange may turn indoor air so dry that negative health effects can result. For example, if outside air with a temperature of 0°C and 60% relative humidity enters a room and is heated to 20°C, its relative humidity decreases to less than 20%. Even if the outside air (temperature 0°C) had 100% humidity level and was warmed up to 20°C, its relative humidity would still drop to less than 30% [1]. In both cases, it becomes necessary to raise the humidity as soon as possible in order to attain healthy and comfortable conditions. This can be done by regulating the humidity that is released by walls, ceilings, floors and furniture. A basic scheme of this is shown in the figure 4 which is a simple Carrier diagram:

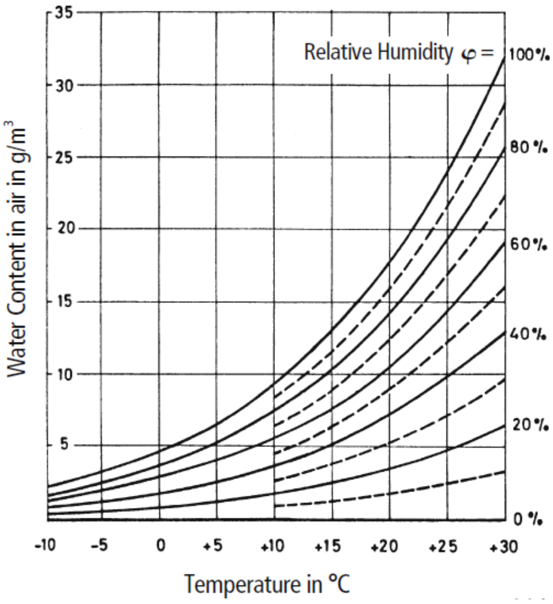


Figure 4: Carrier diagram. Source: *Building with earth Design and Technology of a Sustainable Architecture*

The balancing effect of loam on humidity

Porous materials have the capacity to absorb humidity from the ambient air and to desorb humidity into the air, achieving humidity balance in indoor climates. The equilibrium moisture content depends on the temperature and humidity of the ambient air. The effectiveness of this balancing process also depends upon the speed of the absorption or desorption. Experiments show, for instance, that the first 1.5-cm-thick layer of a mud brick wall is able to absorb about 300 g of water per m^2 of wall surface in 48 hours if the humidity of the ambient air is suddenly raised from 50% to 80%. However, lime-sandstone and pinewood of the same thickness absorb only about $100\ ^{g}/_{m^2}$, plaster $26\ to\ 76\ ^{g}/_{m^2}$, and baked brick only $6\ to\ 30\ ^{g}/_{m^2}$ in the same period [1]. The absorption curves from both sides of 11.5-cm-thick unplastered walls of different materials over 16 days are shown in the figure 5:

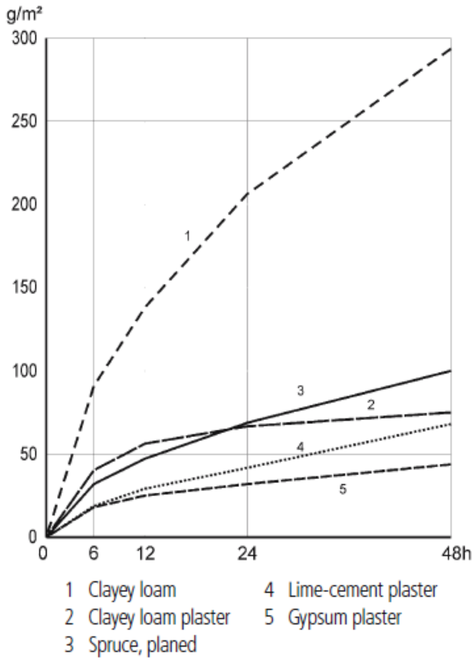


Figure 5: Absorption of samples, 15 mm thick at a temperature of 21ºC and a sudden increase of humidity from 50% to 80%. Source: *Building with earth Design and Technology of a Sustainable Architecture*

The results show that mud bricks absorb 50 times as much moisture as solid bricks baked at high temperatures. Measurements taken over a period of five years in various rooms of a house built in Germany in 1985, all of whose exterior and interior walls were built of earth, showed that the relative humidity remained nearly constant over the years, varying from 45% to 55%. The owner wanted higher humidity levels of 50% to 60% only in the bedroom [1]. It was possible to maintain this higher level (which is healthier for people who tend to get colds or flues) by using the higher humidity of the adjacent bathroom. If bedroom humidity decreased too much, the door to the bathroom was opened after showering, recharging the bedroom walls with humidity.

Influence of heat

The perception that earth is a very good material for thermal insulation is unproven. A solid wall of rammed earth without straw or other light aggregates has nearly the same insulating effect as a solid wall of baked bricks. The volume of air entrained in the pores of a material and its humidity are relevant for the thermal insulation effect. The lighter the material, the higher its thermal insulation, and the greater its humidity level, the lower its insulating effect. The heat flowing through a building element is defined by the overall heat transfer coefficient U.

The heat transfer of a material is characterised by its thermal conductivity K, this indicates the quantity of heat, measured in $watts/_{m^2}$, that penetrates a 1-m-thick wall at a temperature difference of 1ºC.

Thermal conductivity

Thermal conductivity is the property of a material to conduct heat. Heat transfers higher in materials with higher thermal conductivity than lower's. It is measured in $\frac{Watt}{kg{\cdot}Kelvin}$

A thermal conductivity of $1\ \frac{Watt}{kg{\cdot}Kelvin}$ indicates the amount of Jules passed through a surface of one square meter, with one meter thick, when the temperature differences between the two surfaces is one Kelvin degree in one second, is equal to one.

The thickest the material, the lower the heat transferred, and the lower the thermal conductivity (λ) the better for thermal insulation.

According to AIRAH 2000 [4], the thermal conductivity of a 250 mm thick of rammed earth wall with a density of $1540\ {kg}/_{m^3}$ and a specific heat of $1260\ \frac{J}{kg{\cdot}K}$ is $1.25\ \frac{W}{kg{\cdot}K}$.

What we are looking for when we build a building is a material with low thermal conductivity so then, the temperature remains more less constant in the inside of the building.

The case of earth, as usually the structures are very thick, the thermal conductivity is low, so then the heat transfer is low too. That is why are so good with thermal insulation.

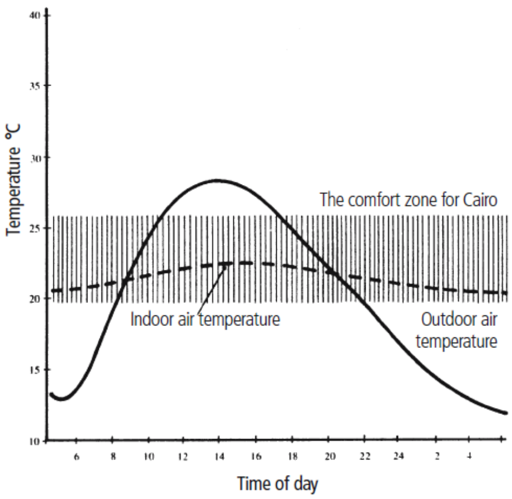
Fire resistance

According to the German Standard DIN 4102, loam, even with some straw content, is not combustible if the density is higher than 1700 ${kg}/_{m^3}$. [1]

Decrement factor and time lag

Decrement factor and time lag refer to the way the exterior wall of a building reacts to damp and to period of delay before outside temperatures reach the interior. A wall with a high thermal storage capacity creates a large time lag and heat decrement, while a wall with high thermal insulation reduces only temperature amplitude.

In climates with hot days and cold nights, where average temperatures lie within the comfort zone (18ºC to 27ºC), thermal capacity is very important in creating comfortable indoor climates. This is shown in the following example:



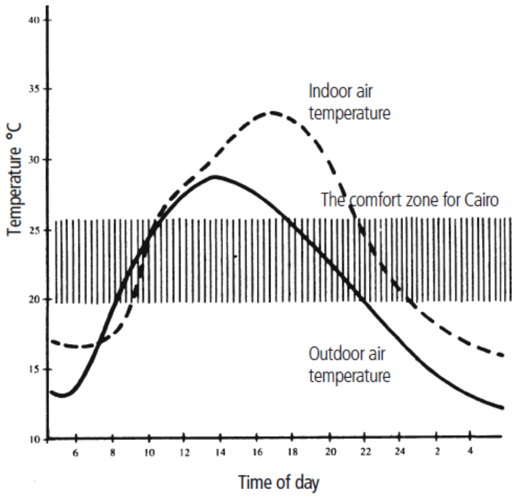


Figure 6: Comparison of indoor and outdoor air temperature of a building with adobe vaults (left) with one using prefabricated concrete slabs (right) (Fathy, 1986). Source: *Building with earth Design and Technology of a Sustainable Architecture*

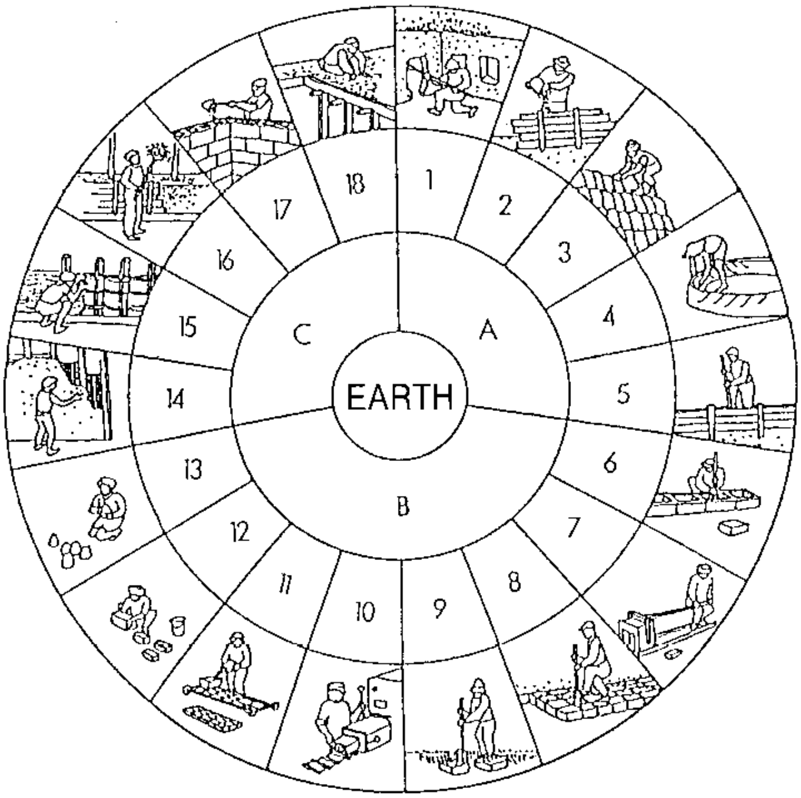
Figure 6 show the results of two different test buildings of equal volume constructed in Cairo, Egypt in 1964. One was built of 50-cm-thick earth walls and mud brick vaults, and the other of 10-cm-thick pre-cast concrete elements with a flat roof.

We can see that the temperature on the inside on the building has almost no variation in the building made out of earth whereas the concrete one, has a variation similar to temperatures outside.

This shows how good can be the earth construction for temperature regulation, whereas in the concrete building the range of inside temperatures is about 15ºC, the variation on the earth one is less than 5ºC. This is translated into less energy costs for air conditioning or heaters and more comfortable temperatures through all day.

Earth construction methods

There are different techniques with the use of earth for building, many variants of treating the earth for rising a structure, there are ways even of using earth just as a part of the structure with no structural purposes. The different uses on earth are shown in figure 7:



A - The use of unbaked earth in monolithic load-bearing form
1 Earth dug out
2 Poured earth
3 Stacked earth
4 Direct shaping
5 Rammed earth

B - The use of unbaked earth in the form of load-bearing masonry
6 Tamped blocks
7 Compressed blocks
8 Cut blocks
9 Sod
10 Extruded earth
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12 Hand moulded adobe
13 Hand shaped adobe

C - The use of unbaked earth in conjunction with a load-bearing structure
14 Daubed earth
15 Cob on posts
16 Straw clay
17 Fill-in
18 Layered on flat surface

Figure 7: Scheme of different uses of earth for construction. Source: The Courier - N°159 - Sept- Oct 1996 Dossier Investing in People Country Reports: Mali ; Western Samoa

The use of unbaked earth in monolithic load-bearing form.

The following methods are based upon creating a structure with earth in such a way that it is in one-piece shape. The methods are:

Earth dug out

This is maybe the first housing technique used by humanity with earth, due to its structural simplicity. We dug out the earth in a vertical or horizontal way so the resultant hole becomes a shelter for humans or animals.

For complementing this technique, usually something more is needed, a cover for the entrance or stairs if we do it vertically, so then the meteorological conditions cannot affect the inside of the shelter. This cover usually made with basic materials such as timber has not to be very important, as seen on the figure 8, where a shelter is shown whose construction uses wood.

There is also the option of horizontal excavating if we have somewhere to excavate on, such as a hill, as shown on the figure 9. There is also the possibility of combine both methods.

For being able of dug out the earth, the soil must be soft enough and we have to assure the structure will be stable enough, because this method may be very unsafe if something happens during construction, such as in tunnels'.

Figure 8: Dugout home near Pie Town, New Mexico. Source: http://en.wikipedia.org/wiki/Dugout_%28shelter%29#mediaviewer/File:Dugout_home2.jpg

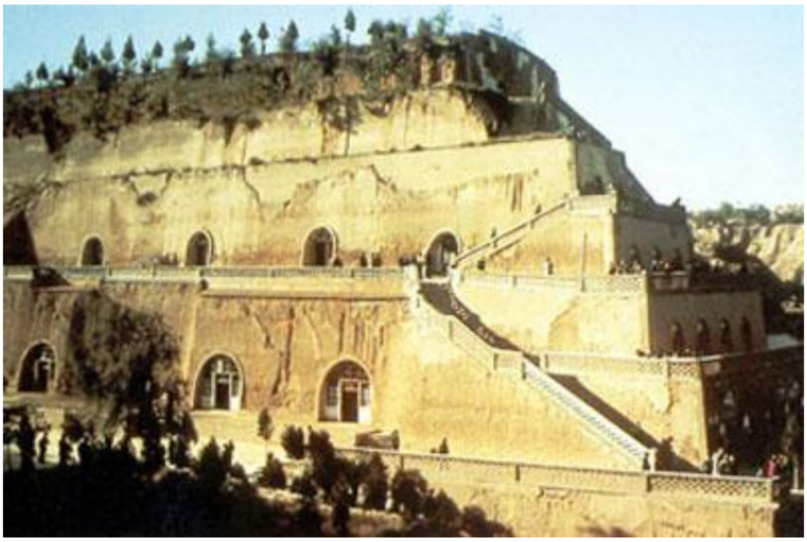

Figure 9: School in China created by horizontal dugout technique. Source: http://www.earth-auroville.com/earth_dug_out_en.php

Poured earth

This method consists in pouring earth on a liquid state into a formwork, just like concrete. For the mixture to be appropriate and have consistence enough we must add a lot of cement and water. Basically the mixture is like concrete but with no standardised earthen components.

This kind of structures may have a lot of shrinkage due to its high water content that is why is not very extended. An example of this construction method is shown in figure 10.

Figure 10: House built with poured earth. Source: http://www.greenhomebuilding.com/poured_earth.htm

Stacked earth

This method, also known as cob, consists in taking soil in plastic state and shape it while it is still wet. Usually cob uses straw as a fibre material.

Stacked earth structures are remarkable for its ease to build and the huge moldability, an experienced worker can create structures such as shown in figure 11 or figure 12.

Figure 11: Structure made with stacked earth in Burkina Faso. Source: http://www.earth-auroville.com/stacked_earth_en.php

Figure 12: Example of Pacific Northwest-style cob home. Source: http://en.wikipedia.org/wiki/Cob_(material)

Direct shaping

As its name says, this method consists in directly shaping the earth on plastic state directly with the use of hands or very basic tools.

In the same way as cob, the resultant structure will depend on the ability of the worker because he knows the amount of water and the plasticity required for the building due to its experience. An example of a construction made with direct shaping is shown on figure 13.

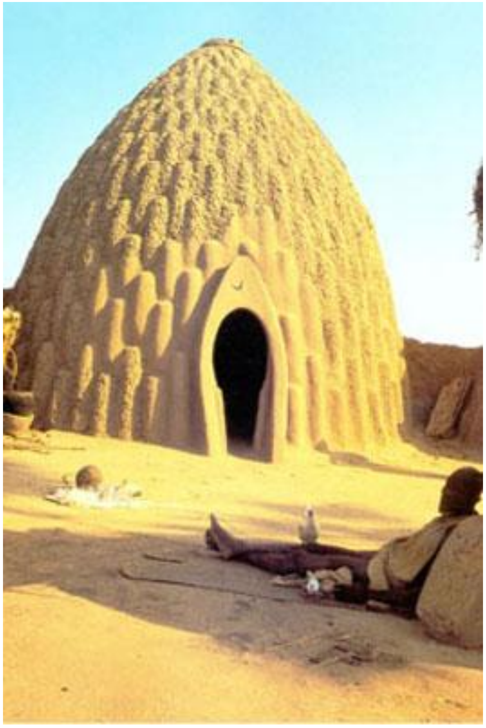

Figure 13: Direct-shaped house in Cameron. Source: http://www.earth-auroville.com/shaped_earth_en.php

Rammed earth

This method consists on setting layers of earth into a formwork and compact it to increase its density and its compressive strength and then repeat again until the top of the structure desired. The density of rammed earth is the highest of the unbaked earth constructions, that is why this method is one of the best's of this kind.

Rammed earth can also be stabilised with additives such as cement to increase its resistance, then is known as Stabilised Rammed Earth and this method is even better than unstabilised one.

Incredible structures can be created with this simple technique, such as shown on figure 14, where the Nk'Mip desert cultural centre, in Canada.

Figure 14: Nk'Mip Desert Cultural Centre, South Okanagan Valley in Osoyoos, British Columbia, Canada. Source: https://inspirationgreen.com/rammed-earth.html

The use of unbaked earth in the form of load-bearing masonry

These categories are based on brick building with earth and additives or fibres and when the bricks are dried, a structure is risen.

Tamped blocks and compressed blocks

This two techniques are similar, they consist in creating soil blocks and then compact them so they achieve better properties.

The difference between the tamped and the compressed blocks is in how they are compacted, the tamped ones, are set in a formwork, such as rammed earth, explained before, and then compacted and the compressed blocs are not compacted but compressed.

The technical difference between one and the other is that compressing means put the soil into some kind of machine or device with the shape of the brick and then applying force to reduce the volume of the initial brick to increase the resistance. A machine like that is shown on figure 15.

Figure 15: Cinvaram, a press for compressing blocks. Source: http://www.earth-auroville.com/compressed_earth_blocks_en.php

Cut blocks and sod

In areas where the local soil is cohesive enough, the soil is cut in blocks and used as a brick or stones for building. The soils which are valid for this method can be:

Soft soils, which will gain strength when they are extracted and react with the air.

Hard crust which long ago was a soil and it has already hardened through years.

If the soil in the nearby is not cohesive enough, we can use topsoil and grass to create blocks which are stacked fresh upon each other, this method is known as sod.

In figure 16 we can see a man working on cutting the local soil into small blocks in Burkina Faso.

Figure 16: Worker cutting blocks in Burkina Faso. Source: http://www.earth-auroville.com/cut_blocks_en.php

Extruded earth

As it works in the fired brick industry, that the mixture is extruded through a press and cut when necessary, the same procedure occurs with unbaked bricks. This bricks have to be created with stabilised earth at a plastic state. The blocks are usually hollowed.

This technique is very modern due to its necessity of mechanical press but has the inconvenient in comparison with the classical fired brick industry that the machines get damaged very quickly due to the composition of the stabilised mixture is often very sandy and this implies much abrasion for the machinery.

In the figure 17 we can observe an extrusion machine of unbaked earth.

Figure 17: Unbaked earth extrusion machine. Source: http://www.earth-auroville.com/extruded_earth_en.php

Machine moulded, hand moulded and hand shaped adobe

Adobe bricks are clay bricks which are left to dry at sun. First we gave them the shape and then are left at sun to dry.

The shape of the bricks depends on the culture of the region and of the ability of the worker but there is also the option of making them with a mould or with a machine.

If it is entirely made by hand without a mould it is considered hand shaped adobe, if it is made by hand but with a mould, hand moulded adobe and if it is made using any kind of machine is name machine moulded.

Machine moulded adobe is very recent technique if we compare it with adobe's origin, which has thousands of years, and the most common device for the construction is shown on figure 18, which cuts the blocks into regular pieces.

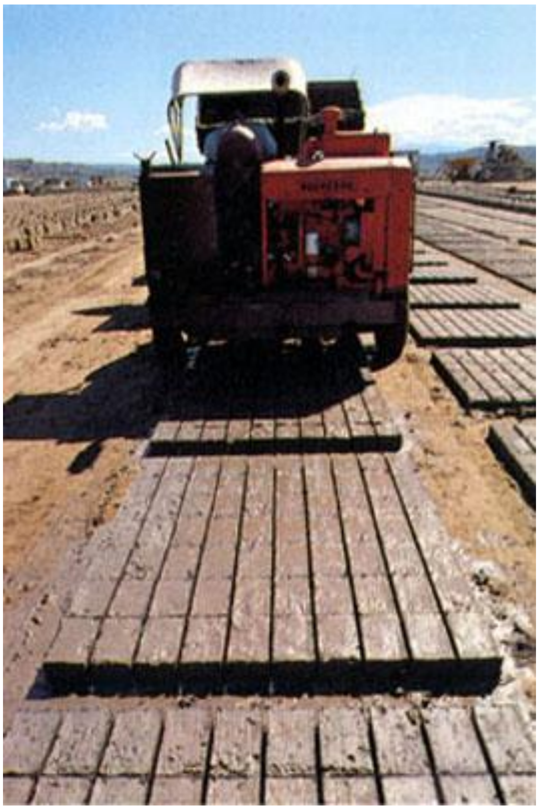

Figure 18: Adobe machine moulder. Source: http://www.earth-auroville.com/adobe_moulding_en.php

The use of unbaked earth in conjunction with a load-bearing structure

The following methods use earth as a component in construction but not as a structural material. The techniques are diverse and use earth due to its properties, explained previously in this document.

The idea is to use the properties of earth, and in some cases its weight, but not its structural resistance.

Daubed earth (wattle and daub) and cob on posts

A load structure made with different materials, generally wood, is closed with infill wall panels, called wattle, afterwards the material is covered (daubed) with a mixture of wet soil, clay, sand, straw, anything that could be useful.

An example of a construction of this style is shown in figure 19.

The cover can be done with cob, previously explained material.

Figure 19: Construction of a daubed earth house in Somalia. Source: http://www.earth-auroville.com/wattle_and_daub_en.php

Straw clay (formed earth)

Clayey soil, in liquid state, is poured on straw and tampered into forms. The resultant walls are light and with high thermal insulation, but they are not load-bearing.

These walls can be used as a filler walls, formed between a wooden structure or as prefabricated blocks.

On figure 20 we can see an example of a house built with this technique.

Figure 20: House built with straw clay in Germany. Source: http://www.earth-auroville.com/formed_earth_en.php

Fill-in

This is the most basic of the methods for using the properties of earth but its strength. There are two different methods:

The first is to build two parallel walls, with any material and equidistant some centimetres, and fill the space between with earth. This is the most basic and easy one.

The second is more modern, it consists in pouring dry soil into synthetic textiles with different forms and then this bags are used in construction. There is an example of this on figure 21, where long tubes are filled with soil and then with several tubes, the shape of the structure is made.

Figure 21: Two workers rolling a tube with earth inside, USA. Source: http://www.earth-auroville.com/earth_filled_in_en.php

Layered on flat surface

This technique is about covering the roof of a house or building with earth, and usually grass or weed is put in to increase the cohesion to it with its roots.

The objective is to, due to its high thermal mass, regulate the inside temperature but also in cities, help with pollution issue by adding some plants into the town. Having soil in the roof also is good to mitigate the problem of urbanisation on water quality by absorbing or detaining rainfall.

Figure 22 shows an example of a school in Germany with its roof protected with this technique, and figure 23 a house in Feroe Island with the same method used.

Figure 22: School in Germany with soiled roof. Source: http://www.earth-auroville.com/covered_earth_en.php

Figure 23: House with grass roof in Feroe Island. Source: http://101lugaresincreibles.com/2008/06/las-ciudades-de-los-techos-de-hierba.html

After seeing all this construction techniques, we conclude that the best choice for earth building is rammed earth if we consider the following advantages:

With the use of rammed earth, we have no transportation of material, we use the in-situ soil, we have to remove the first 40-50 cm on the surface due to its presence of hummus (as it will be explained later) but the meters the material has to be moved is none.

For the reason of zero transportation, the costs of rammed earth buildings are very low.

The compaction of the soil gives the structure enough strength to resist all the stresses required. Is the earth construction method with highest strength resistance among the explained. Among the methods explained of earth building, the safest ones are adobe and rammed earth and between this two, the resistance of the rammed earth is higher.

As explained before, the properties of earth for the humidity inside the building make it an ideal material for house building.

The thickness of the material is ideal for soundproofing,

Is a sustainable material which can be used as many times as we want. The formwork used, can be used during a long period of time without changing it, so it is another advantage.

We do not have to wait for drying for the structure or the pieces, like adobe has.

For all this reasons, we have chosen rammed earth for this project/thesis, and now we will get in detail in how it works and some experiments on it.

Building with rammed earth

Building a rammed earth wall involves compressing a mixture of soil with appropriate proportions of sand, gravel and clay into an external formwork or mould. Once this formwork is removed what is left is a block or an entire wall.

The mixture of soil is the most important factor in rammed earth construction because changing the proportions of sand, gravel and clay, the results we obtain differ a lot. It is important to say that to this mixture is compulsory adding water to then the compaction is more efficient, and the Optimum Moisture Content of water will also be a determinant factor in rammed earth building.

Sometimes we add some stabiliser to the soil mixture such as cement or asphalt emulsions in order to improve the properties and the quality of the wall.

The first step in rammed earth building is the preparation of a temporary formwork which can be a traditional type which is used to make small blocks or a big one which will allow us to make the entire wall is one simple step. The structure of the formworks will be explained later in this work.

When the formwork is collocated we throw the damp material inside in a 10-25 cm layer, we extend it uniformly and then we compact it until it reduces approximately to 50% of its original height. This compaction traditionally is done by hand but nowadays in many constructions is done with pneumatic tampers. This process is repeated until the formwork is full of soil.

Once the mould is full, we proceed to remove it. Contrary to other constructions the removal is done just after the last compaction because we suppose the structure has gained strength enough to support it by itself. This process has to be done carefully and we usually put some kind of oil, or mortar in the mould so then the removal takes no risk of break.

When we have removed the mould, we proceed to prepare it for another block, usually next to the one we just built or above it and the process is repeated until the wall is finished. Sometimes after finishing we apply a surface texture.

Now I will explain in detail all these steps, how are they used and the techniques we have to determine the properties of the loam.

Composition of earth

We have seen until now the characteristics of what earth can offer us for building construction, such as humidity and temperature balancer. Now we will see for making a proper good building with earth, which are the variables we have to consider such as percentages of sand, silt and clay, the grain size distribution, humidity, density, etc.

Loam is product of erosion from rock. This erosion happened due to glacier movements, water, wind and other factors such as thermal expansion of water inside rocks or organic activity. The properties and composition of the loam will depend on local conditions. Loam is composed of a mixture of clay, silt, sand and sometimes larger aggregates. Engineering defines this particles according to its diameter:

Smaller than 0.002 mm are called clay.

Between 0.002 mm and 0.06 mm are silts.

Between 0.06 mm and 2 mm are sands.

Larger particles than 2 mm are classified as gravel and stones.

Like cement in concrete, clay acts as a binder is the loam and silt and sand act as fillers. Depending on the percentages of this three components we will classify the loam as clayey, silty or sandy loam. In traditional soil mechanics if clay content is less than 15% of the weight, the soil is poor clayey soil and if it is more than 30% is a rich one. Components with less than 5% of composition in the mixture are not mentioned. For instance: a rich silty, sandy, lean clayey soil contains more than 30% silt, 15% to 30% sand and less than 15% clay with less than 5% of gravel and rock [1].

Even though in earth construction the percentages of components acquires different notation because a loam with 14% clay would be considered a poor clayey soil in soil mechanics and in rammed earth construction would be considered a rich one.

Particle size distribution

The easiest way to characterise the grain size of the loam is with a percentage-passing graph. Is a simple graph where the vertical axis represents the weight that passes through a sieve in percentage and the horizontal axis shows the diameter of the sieve represented into logarithmic scale. The curve is represented cumulatively, with each grain size including all the fine components. An example of this type of graph is shown on figure 24:

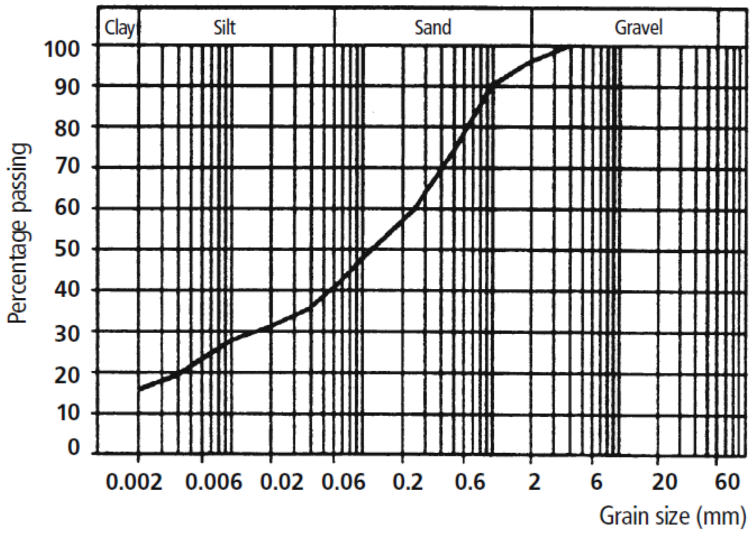

Figure 24: Soil grain distribution of loam with high sand content. Source: *Building with earth Design and Technology of a Sustainable Architecture*

Figure 24 shows a sandy loam with about 15% of clay, 25% of silt and 55% of sand.

In some literature appears what is called an "ideal distribution curve". This curve has been developed in order to minimise the voids ratio for increasing the contact between soil particles. Theoretically soils with no voids can be achieved if the soil particles are entirely spherical and their distribution follows the Fuller Formula, the equation 4 [3]:

$$p = 100 \cdot \left({}^{d}/_{D} \right)^{n} \tag{4}$$

Where:

p is the proportion of grains of a given diameter

d is the diameter of grains for a given value of p

D is the largest grain diameter

n is the grading coefficient

When the grains are entirely spherical, n is equal to 0.5 but in earth construction a value between 0.2 and 0.25 is more appropriate depending on grain shape. In reality it is virtually impossible to find natural soils that match such an ideal distribution.

Figure 25: Example of different standard sieves. Source: http://www.impact-test.com/

Organic constituents

Soil extracted from less than 40 cm from the surface usually contains plant matter and hummus. Earth as building material should be free of hummus and plant matter. Under certain conditions, plant matter like straw can be added, provided it is dry and there is no danger of lateral deterioration.

Density

The density of a soil is defined by the ratio of dry mass to volume. Fresh soil has a density of $1000\ {}^{kg}/_{m^3}$ to $1500\ {}^{kg}/_{m^3}$ but if we compress it, as we do with rammed earth construction, the density increases until $1700\ {}^{kg}/_{m^3}$ to $2200\ {}^{kg}/_{m^3}$. It could be even higher depending on larger aggregates and its density.

Water and its effects

Without water the binding forces of loam are useless. Apart of free water, there are three different types of water in loam: water of crystallisation, absorbed water and water of capillarity. The first one is confined and it's only relevant if the loam is heated more than 400ºC. Absorbed and capillary water are released if the mixture is heated more than 105ºC.

If dry clay gets wet, it swells because water creeps between its lamellar structure. Water surrounds the lamellar structure with a thin film of water. When this water evaporates, this distance is reduced and the lamellar structure of clay are arranged in parallel pattern due to electrical forces. Thus is how clay acquires its binding force.

When loam becomes wet, it swells and changes from solid state to plastic one. When drying, the opposite happens, it shrinks.

Swelling and shrinkage are disadvantageous for building construction. Swelling only happens when a big amount of water gets in contact with loam and it loses its solid state, the absorption of humidity from the air will never be as huge as necessary for swelling.

Swelling and shrinkage depend on the type and amount of clay (Montmorillonite's effects are higher than others like Kaolinite) and the grain distribution.

Determination of linear shrinkage.

According to The German Standard DIN 18952 the procedure for determining the linear shrinkage is as it follows: [1]

1. The dry loam mixture is crushed and sieved to eliminate all particles with diameters larger than 2 mm.

2. About 1200 cm^3 of this material is slightly moistened and hammered on a flat surface to produce a continuous piece (like a thick pancake).

3. This is then cut into 2-cm-wide strips, placed edge-to-edge touching each other, then hammered again. This procedure is repeated until the lower part shows an even structure.

4. Loam with high clay content must then rest for twelve hours, and one with low clay content for about six hours, so that the water content is equally distributed throughout the sample.

5. From this mixture, 200 g are beaten, to compact into a sphere.

6. This ball is dropped from a height of 2 m onto a flat surface.

7. If the diameter of the flattened surface thus formed is 50 mm, standard stiffness is said to be reached. The difference between the largest and smallest diameters of this disc should not be more than 2 mm. Otherwise the whole process must be repeated until the exact diameter

in the drop test is reached. If the disc diameter is larger than 50 mm, then the mixture has to be dried slightly and the whole process repeated until the exact diameter is attained.

8. If the diameter of the disc is less than 50 mm, then a few drops of water should be added. With this standard stiffness, the shrinkage test is to be executed as follows:

1. The material is pressed and repeatedly rammed by a piece of timber about 2 x 2 cm in section, which rests on a flat surface.

2. Three samples have to be made and the form has to be taken off at once.

3. Template marks at a distance of 200 mm are made with a knife.

4. The three samples are dried for three days in a room. They are then heated to 60°C in an oven until no more shrinkage can be measured. The DIN mentions that they are to be dried on an oiled glass plate.

5. The average shrinkage of the three samples in relation to the length of 200 mm gives the linear shrinkage ratio in percentages. If the shrinkage of one sample differs more than 2 mm from the other two, the sample has to be remade.

Drying period

The period during the loam reaches its equilibrium moisture content is called drying period. The decreasing water content and increasing shrinkage of a sandy mud mortar dried in a closed room at a temperature of 20ºC with a relative humidity of 81% and 44% is shown in the figure 26 [1]:

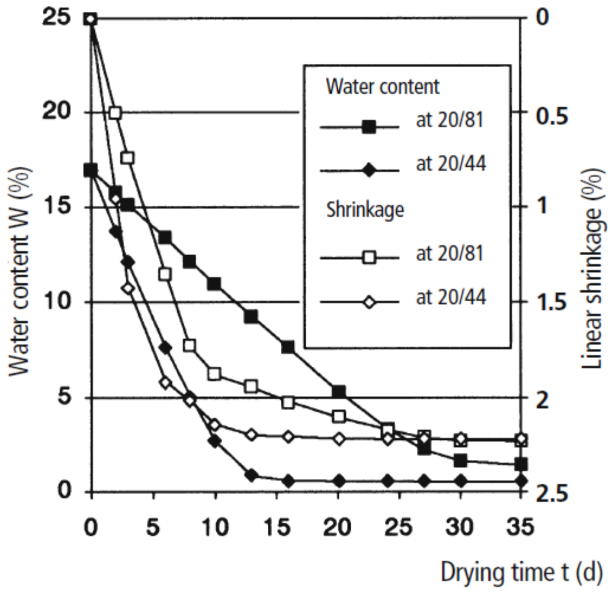

Figure 26: Linear shrinkage and drying period of lean loam mortar (clay 4%, silt 25%, sand 71%) with a slump of 42 cm according to German Standard DIN 18555 (Part 2). Source: *Building with earth Design and Technology of a Sustainable Architecture*

With 44% humidity, the drying took 14 days while with 81% humidity it took about 30 days.

In figure 27 is shown the drying process of different loam samples compared to other building materials, test ran by BRL.

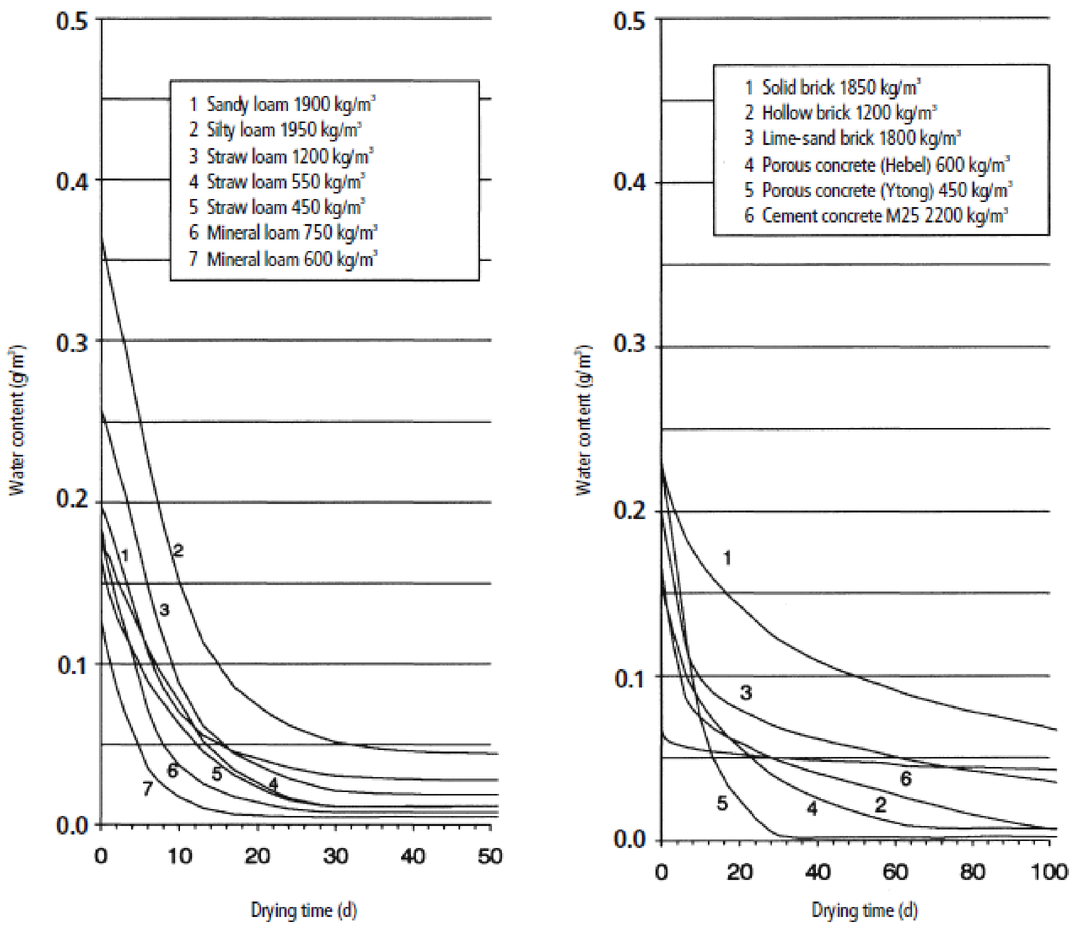

Figure 27: Drying period of loams and other building materials. Source: *Building with earth Design and Technology of a Sustainable Architecture*

Figure 27 show that all earth materials dried in about or less than 30 days while baked bricks or concrete materials, take longer time to achieve the equilibrium.

Compactability

Is the ability of earth to reduce its volume by pressure (static or dynamic). The maximum compaction is achieved with an specific water content, the Optimum Water Content, which allow particles to move in a more dense state without too much friction. The optimum water content is measured with the Proctor Test:

The Proctor Test will determine the optimum moisture content and the maximum dry density of soils for rammed earth, the procedure is very simple and standardised:

A soil sample of known moisture content is compacted in 1-litre cylindrical mould, compaction is carried out in 3 to 5 layers of equal thickness by dropping a weight falling 27 times on each layer from 300 mm or 450 mm. When the cylinder is ready, the wet height is recorded and then the sample is left to dry. We should prepare at least 5 samples at various moisture contents. When the samples are dry, we calculate the moisture content and the dry densities and we plot the results on a graph. From the resultant curve, it is possible to determine the optimum moisture content.

An example of Proctor test results is shown on figure 28:

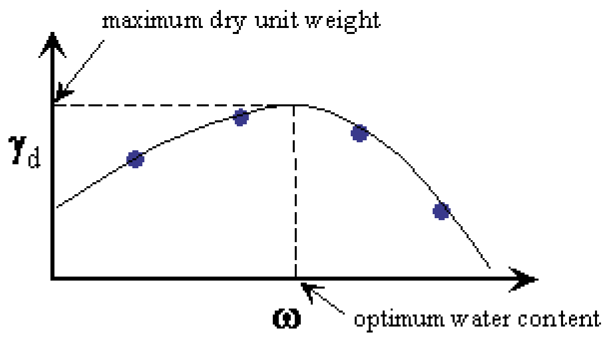

Figure 28: Results of a standard Proctor Test. Source:
http://www.naturalbuildingblog.com/proctor-soil-compaction-test/

As we can see on figure 28, the maximum dry unit weight increases with water content until certain point, after this point, the addition of water is nothing but damaging for the sample. This is why is good to know the optimum water content, to obtain the best results.

Nowadays, rammed earth is usually stabilised with some additives, mostly cement and research has shown that the optimum water content differs a little with unstabilised rammed earth.

A recent experiment performed by the university of Western Australia [7] showed that the optimum water content for a sample of rammed stabilised with cement (maintaining the OWC), is not the same as the one without it.

This is apparently no rare, clearly adding something (cement) to the mixture will modify the optimum water content. The result is that the final result of the experiment was that with a water content, lower than the optimum, the resistance is the highest.

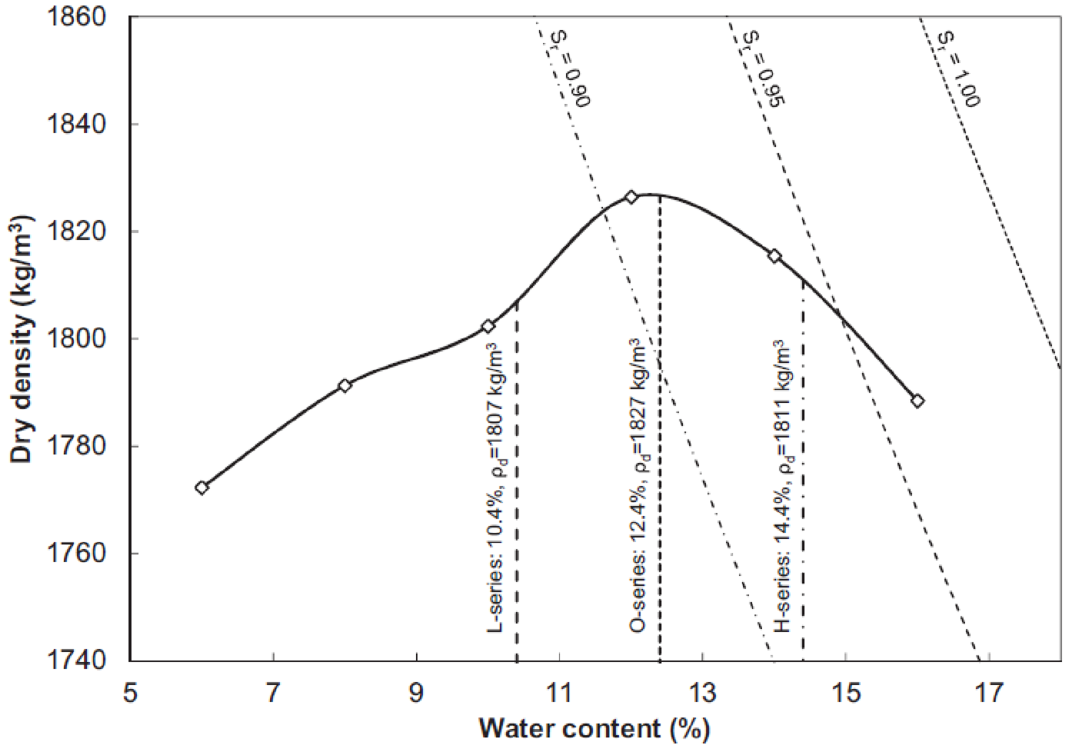

Figure 29: Optimum water content of the unstabilised sample. Source: *Effect of compaction water content on the strength of cement-stabilised rammed earth materials*

As can be shown on figure 29, in the experiment performed, they had already calculated the OWC, as explained before, and after adding cement to the mixture, they decided to create samples with 2% more than the optimum and samples with 2% below OWC. The results are shown on figure 30, where the L-series, is the one with 2% less water content that should be, the O-series, the series with the theoretical optimum water content, and the H-series, with 2% higher.

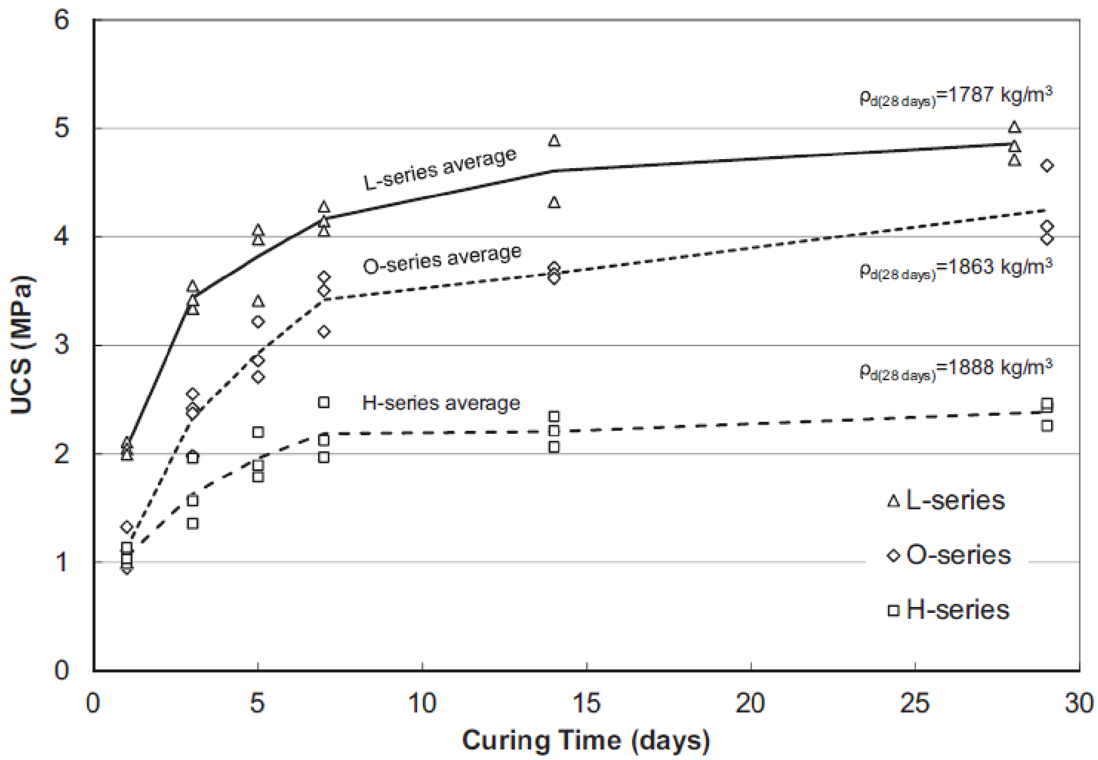

Figure 30: Unconfined compressive strength results for three series versus curing time. Source: *Effect of compaction water content on the strength of cement-stabilised rammed earth materials*

In figure 30 we can see that the result is that the series with lower water content are the most resistant as time goes through, so it may be important to check the OWC of a stabilised rammed earth before building any structure, or at least have into consideration this result: better not adding more water than the OWC, because it loses much of its strength.

Tests used to analyse the composition of the loam

For checking the properties explained before we have different methods. Some of the methods are designed for being realised in a laboratory with specific machinery and devices but there are some developed through experience, much simpler for being done in the field. This really are the tests the worker will always do to check whether the loam is of good enough quality or not and if it is able for construction even though there are not very exact. Laboratory tests are not really of much use except for important projects or for research.

Sedimentation test or Jar test

The mixture is shake with water in a glass jar, we left it to stand for an hour and then is shaken again. The largest particles will settle at the bottom, the finest at the top. This stratification allows the components to be estimated. The best results are after eight hours of precipitating. We cannot ensure the result of this test will proportion us the exact proportion of clay, silt and sand, as a matter of fact, several experiments have shown that the margin of error of this test could even be as large as 1500%. That is so because we can only distinguish sudden changes of grain-size distribution and these may not coincide with actual defined limits between clay and silt, and between silt and sand [1].

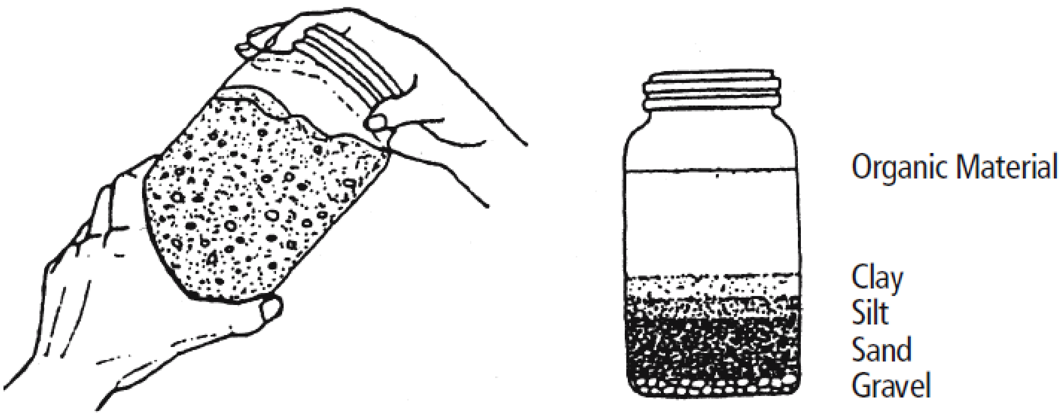

Figure 31: Sedimentation test. Source: *Building with earth Design and Technology of a Sustainable Architecture*

Water content.

The percentage of water is very important to be determined of a mixture and the method for determine it is very simple: we weight the wet loam and the dry one and we prepare a percentage to show it. For drying the sample of loam is only needed an oven which can reach temperature of 105ºC and a balance. Afterwards we make the percentage.

Consistency test.

Moist earth is formed into a ball 2 to 3 cm in diameter. This ball is rolled into a thin thread 3mm diameter. If the thread breaks or develops large cracks before it reached 3mm diameter, the mixture is slowly moistened until the thread breaks only when its diameter reaches 3mm.

The mixture is then formed into a ball. If this is not possible, then the sand content is too high and the clay one, too low. If the ball can be crushed between the thumb and the forefinger with only with force, the clay content is high and has to be thinned by adding sand. If the ball crumbles very easily, the loam contains a little clay [1].

Ball dropping test.

The mixture to be tested has to be as dry as possible but wet enough to be formed into a ball of 4 cm diameter. When this ball is dropped onto a flat surface from a height of 1.5 meters, various results can occur, as shown in the figure 32:

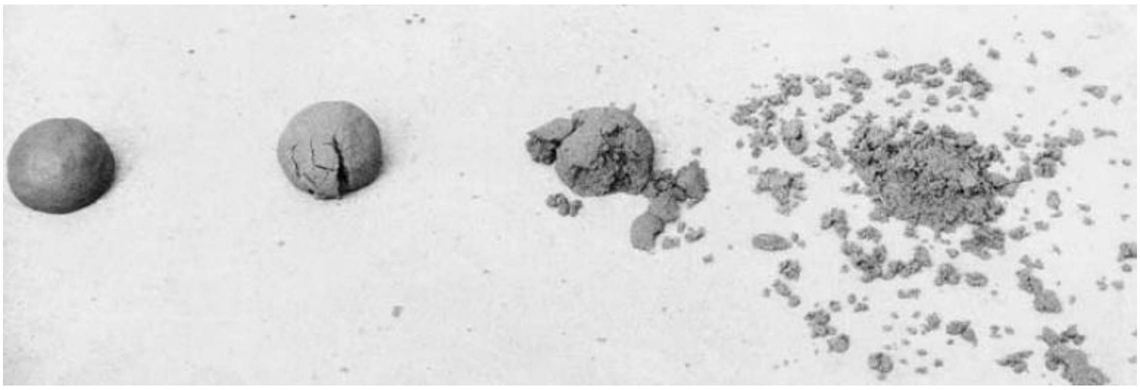

Figure 32: Loam balls after the dropping test. Source: *Building with earth Design and Technology of a Sustainable Architecture*

If the ball flattens only slightly and shows few or no cracks, like the sample on the left of figure 32, it has a high binding force due to its high clay content. Usually this mixed has to be thinned, adding some sand. If the sample looks like the one in the right in figure 32, it has low clay content, its binging force is probably not sufficient and it will not be appropriate as a building material. The other sample in figure 32 has relatively poor binding force but its composition usually enables it to be used for rammed earth constructions [1].

Cohesion test (ribbon test)

The loam sample should be just moist enough to be rolled into a thread 3 mm in diameter without breaking. From this thread, a ribbon approximately 6 mm in thickness and 20 mm wide is formed and held in the palm. The ribbon is then slid along the palm to overhang as much as possible until it breaks.

If the free length before breakage is more than 20 cm, then it has a high binding force, implying a clay content that is too high for building purposes. If the ribbon breaks after only a few centimetres, the mixture has too little clay [1].

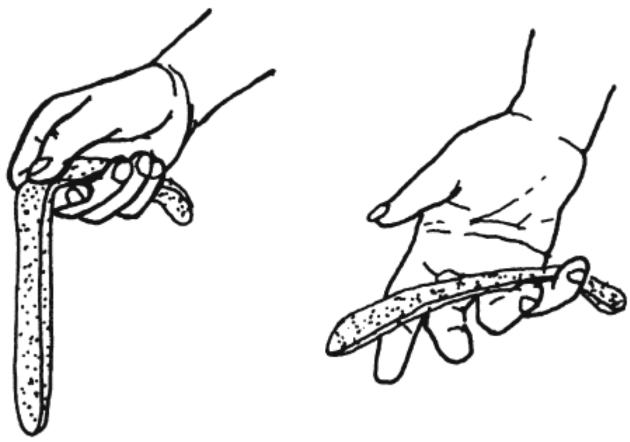

Figure 33: Ribbon test. Source: *Building with earth Design and Technology of a Sustainable Architecture*

Strength of earth as a structural material

After explaining all the properties earth can have for building that can be advantageous or unfavourable and all the components it has and its composition we need to focus on the most important factor, its resistance.

Few can we achieve with all its properties if a structure of earth cannot support the efforts it requires. We need a minimum strength for it to make the difference between a building material and a decorative or furniture construction one.

Rammed earth is used only in compression because its strength as a tension material is very poor, such as it happens to concrete. The mechanical strength of a soil is much dependent on the voids ratio of the soil after ramming, cohesive strength of fines content, aggregate strength and moisture condition during testing. Density of the soil is very important for the strength as well.

The compressive strength of dry elements of earth are usually from 5 to 50 $^{kg}/_{cm^2}$. This depends not only on the quantity and type of clay involved, but also on the grain size distribution of silt, sand and larger aggregates, as well as on the method of preparation and compaction.

The tensile strength of a dry material made of earth is of no relevance because earth structures must not be under tension. Dry tensile strength is about 10% of compression one [2].

According to Australia standards which are one of the most advanced ones referent to rammed earth constructions, the bending strength and the shear strength of walls or other earth structures will be taken equal to zero unless the is a specific test performed for this particular structure where this efforts may be taken in consideration.

As mentioned before, we can improve properties of rammed earth by adding additives to the loam moisture, such as cement. The most relevant reason for adding components is the increase of strength of the structure, and the results are significant, now I will expose how the rammed earth samples are fabricated in a laboratory according to standards and then expose some results of experiments around the world regarding to rammed earth resistance, composition and additives and which conclusions can we rely on after them.

Fabrication of samples of rammed earth in a laboratory [5]

The following technique is based upon specifications in NZS 4298: 1998, New Zealand's standardisation, a country where the rammed earth building is very extended so the legislation on this field is very advanced.

The methodology proposed may seem to have many similarities with the Proctor test, previously mentioned for obtaining the optimum moisture content of water in a soil sample. NZS 4298: 1998 states that for rammed earth samples, the water content should not be 5% above the optimum neither 3% lower than it.

First we will need to select the loam sample we want to evaluate. The choice of the sample may depend clearly on the purpose of the experiment, for example, if we want to evaluate the resistance of the soil of a determinate zone for building there, we will take the sample for over there but in case we want to create samples for experimentation and research we may want to have a specific grain distribution-size curve, therefore we can select it manually if we have samples of each particle size and prepare the calculations of weight for the precise curve or it what we want is not that accurate we may use the following method:

What is common in laboratories of rammed earth is having three different soil samples such as granular soil sample, only formed by gravel, one by cohesive soils (silt and clay) and finally the intermediate sample with sand. This different samples of soil are not precise when to particle size distribution means, so for example the sand samples can have diameters from 0.06 mm to diameters of 2 mm and the silt can vary between 0.002 mm to 0.06 mm.

With this three types of soil, we will prepare the mixture adding certain proportion of each sample, having a percentage of mass of each of the three we will name with a three digit number, for example:

Sample 532:

5 kg of sand

3 kg of gravel

2 kg of clay.

The badge is of 10 kg so the number of kilograms correspond to its ten-percentage.

The soils are oven dried.

Once we have the sample we are going to use, we may want to do the sieving test for knowing exactly the particle-size distribution curve, as explained previously.

In the figure 34 we can see many samples created with this method which have gone through the sieve test. The curve IDEAL is the one mentioned previously:

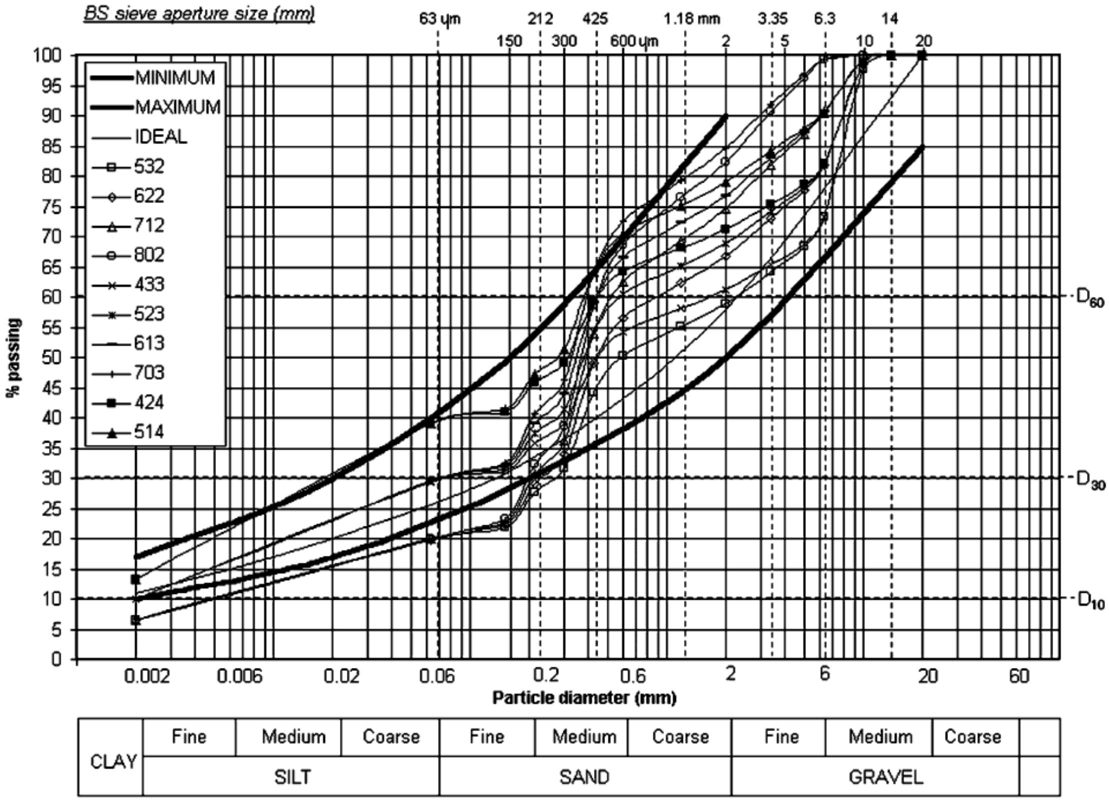

Figure 34: Particle size distribution chart with rammed earth soil data. Source: *Rammed Earth sample production: context, recommendations and consistency.*

After weighting the sample, we pulverise the silty clay and after mixing it with water to obtain the desired water content, we proceed to mould it.

In this test we want to replicate as much as possible the reality so we will ram the sample with a manual rammer that weights $6.5\ kg$ and with a ramming surface of $98x98\ mm$. The mould we are going to use is a cubic concrete mould that will contain a litre of sample after compacted, $100x100\ mm$.

The mould will be painted with oil inside and then we throw the soil inside, about one third of the height of the mould and then compact it, we repeat the process 2 more times until we have the entire mould filled. Then, as we do it with concrete samples, we will smooth the upper surface with moist soil lower than 2 mm with a spatula in order to create a perfectly flat surface, because we will need two parallel surfaces for the testing.

The samples have to be cured in a sealed curing chamber for at least 28 days at a temperature of $20ºC \pm 1ºC$ and with a relative humidity of $75\% \pm 5\%$, and afterwards we can do several checking of the samples such as measuring its weight so then we obtain the density, we can check if there is visual shrinking and finally, analyse the compressive strength. The procedure for strength evaluation is the same we usually do on concrete, we can even use the same machinery for breaking the samples. In this case we will have to apply a factor if we have created cubic samples, or not if we used cylindrical ones.

For doing this test properly would be convenient to elaborate a large number of samples (minimum 5), it is also convenient that not all the samples we test come from the same badge, in case we did something wrong on it, after breaking the samples we apply the following equation:

$$f = \left(1 - 1.5 \cdot \frac{X_S}{X_A}\right) \cdot x_1 \qquad (7)$$

Where:

f is the characteristic unconfined compressive strength

X_S standard deviation of the series

X_A mean average of a series

x_1 the lowest result

Finally we have to evaluate the results, for example plotting them on a graphic.

The following plot represents an experiment performed in Sheffield University in United Kingdom and shows the relation of dry density of each sample and its resistance from 10 different soil types with the three-digit notation for the badges explained before.

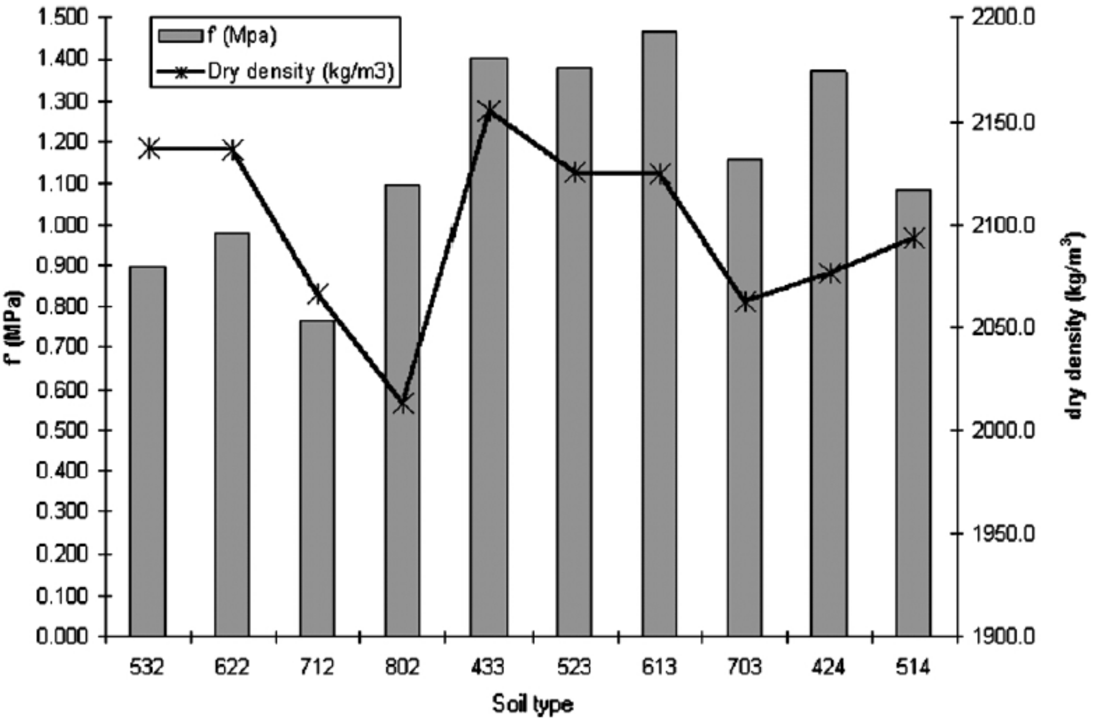

Figure 35: The results of the experiment on each rammed earth soil type. Source: *Rammed Earth sample production: context, recommendations and consistency.*

From figure 35 we can conclude the experiment that was performed wanted to clearly find a direct relation between the dry density and the characteristic unconfined compressive strength, and we can see, there is no relation at all between this two factors.

Durability of earth as a structural material

When we refer to durability of earth as a structural material, we always are talking about its capacity to resist against weather conditions without degradation of the expected service life. Rain and frost are the most destructive natural actions causing erosion and deterioration of earthen elements.

Rainfall erosion

The performance of natural rammed earth under driving rain cannot be readily predicted in the absence of test data. However, at the same time there is a little correlative data between laboratory tests and field erosion. Building element erosion is complicated by various parameters, such as exposure, shelter and maintenance. Two main tests have been developed to measure relative erosion resistance of earth elements, namely water drip tests and spray tests.

The Geelong drip test is a simple assessment test in which water droplets are allowed to impact onto the surface of the test specimen. Initially developed for adobe mud blocks the test can be adopted for rammed earth as well, using specimens $300x300x125\,mm$ thick. Each element is inclined $27º$ from the horizontal and water is released through a $16\,mm$ wide sponge cloth and allowed to fall $400\,mm$ in droplets. One hundred millilitres of water should be released within 20 to 60 minutes of the test commencing and the sample performance is measured in terms of pitting depth and depth of moisture penetration. According to New Zealand Standard, failure of specimen occurs when the pitting depth is greater than $15\,mm$ or the depth of moisture penetration is greater than $120\,mm$ [3].

In the spray test the specimens are subject to a continuous jet of water spray at $50\,kPa$ pressure for $60\,min$ or until a specimen has completely eroded through, whichever occurs first. The $50\,mm$ spray nozzle is $470\,mm$ away from the sample and the exposed soil area is bound by an impermeable shield, leaving uncovered a circular section of either $70\,mm$ or $150\,mm$ diameter. The water spray is temporally stopped every $15\,min$ to allow measurements of the depth of erosion with a $10\,mm$ diameter flat-ended rod. The maximum depth is taken as the rate of erosion for the whole specimen. According to New Zealand Standard, failure of the specimen occurs when the depth of erosion or the depth of moisture penetration is greater than $120\,mm$ [3].

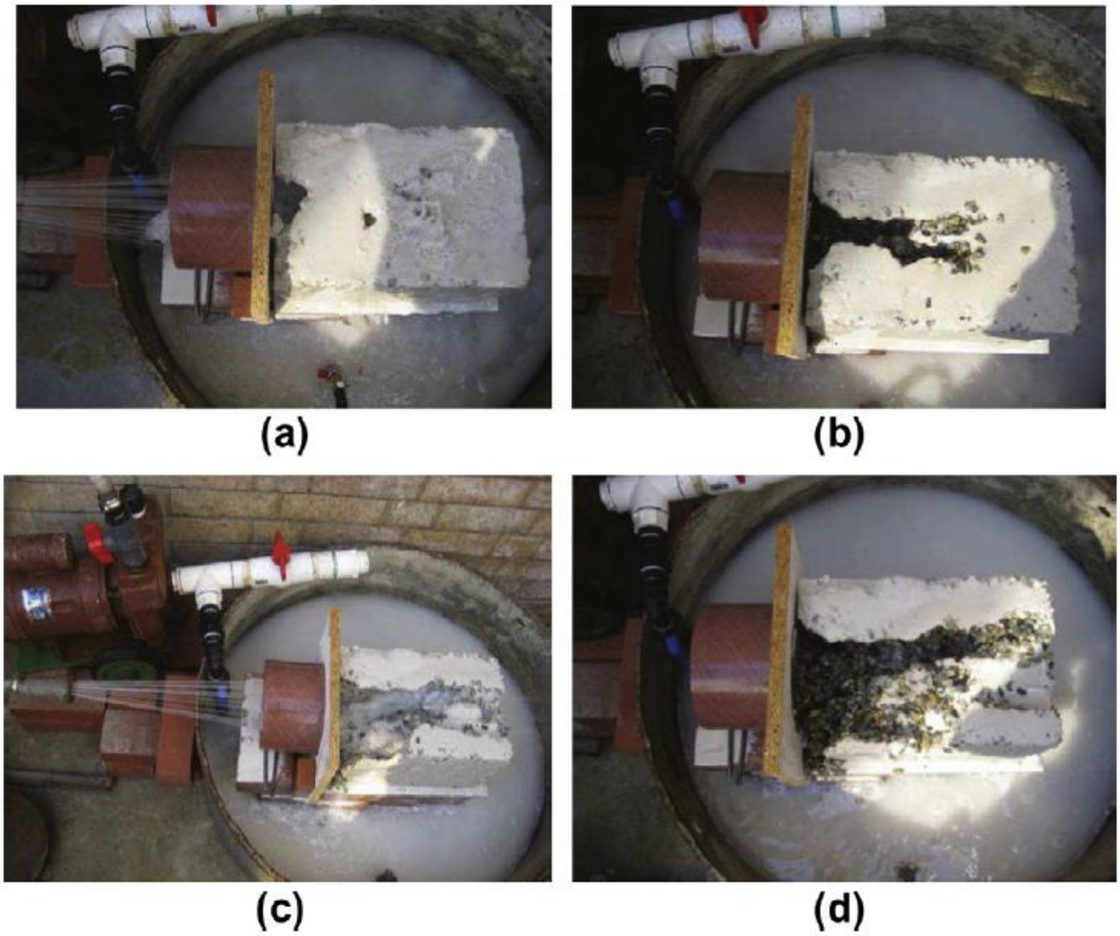

Figure 36: Spray test for 1 sample: Stages a and b near the beginning of the test; c and d at the end of it. Source: *Advances of soil suitability for rammed earth.*

In figure 36 we can observe the evolution of a spray test in a rammed earth sample. This sample did not pass the test, clearly.

There is a lot of criticism of this test because if replies very dissimilar conditions from the real environmental conditions to which a rammed earth wall will be exposed during its life time.

Freeze-thaw deterioration

As in the case of erosion due to the driving rain, the ability of rammed earth to retain integrity when exposed to freezing temperatures cannot be readily predicted. the main test procedure used to assess freeze-thaw durability of rammed earth has been developed by ASTM for soil-cement. The test requires subjecting rammed earth samples to 12 cycles of freezing and thawing whilst the specimens remain saturated. After thawing specimens are subjected to abrasion by a wire brush to remove loosened material. The percentage of mass loss at the end of the test is calculated and if the weight losses are less than the values indicated by the standard used the specimen is considered adequate to produce a durable rammed earth wall. Suitability criteria exist only for soil-cement typically vary between 5 and 14%.

Maintenance and repairs

Seeing how erosion can affect rammed earth walls, it is important to mention what can be done to prevent it, and in case it has already happened, how to deal with it.

The most important factor in order to avoid erosion is a well executed procedure of building, this usually consists in three steps:

1. An adequate base, usually built with concrete, brick or a combination of both, in order to avoid runoff water from the ground eroding the base of the wall.

2. A roof that avoids most part of the rain impact directly into the wall (this is especially needed in zones where rain is an important factor to be considered). This roofs should have pendent enough to let the water flow towards it and protrude some distance off the wall in order to protect lateral rain fall into the wall.

3. An appropriate coating of the wall, in case the measurements previously mentioned fail and rain and other factors make contact with the wall. Surface coatings, renders and plasters have a very important function in protecting the wall against climatic or mechanical actions and also environmental contamination.

Once the wall is built, there is little need of maintenance, at least along the first decades unless something severe happens such an extreme climate of an earthquake. The main maintenance that may be needed is a renewal of the coating in case it suffers from degradation.

The main causes of degradation are: structural strain, lack of ductility, continued access of water, salt contamination, low drying capacity, lack of adhesion to substrate and lack of rendering.

It is not rare to detect problems due to the application of an incompatible render. Renders should be made with materials with similar properties to the wall ones. This is not easy to achieve and the same will happen with plasters for repairs, as it will be explained ahead. It will not be the same situation if we are dealing with unstabilised rammed earth walls or stabilised ones.

Summing up, maintenance should not be a problem if the execution is appropriate and in case there are some actions needed, it will be a renewal of coating occasionally, what is not a big issue.

The case of repairs is not hard to deal with. In rammed earth walls, when we refer to repairs, we are referring to surface degradation, a higher level of degradation would be having a fissure, and a fissure cannot be repaired without a huge production (we are not going to discuss it, because in this cases, the most common diagnose is ruin and there is no possible repair).

When we refer to surface degradation, we have two main types: deep voids and irregularity with loss of cohesion.

Both cases have to be treated with a repair mortar, that will be specifically designed for the structure.

Mortars are all earth-based and must have a binding agent that can only be clay, lime or cement.

Mortars will be composed on one or other component depending on the surface that needs to be treated because the most important characteristic on the mortar is its adherence. The adherence of the mortar towards the surface will be presumably better if it is composed by similar components than the original wall.

It seems obvious that cement, as it is the best binder, it will work always better, and this is not the case. As it is known, cement soaks up water when drying and when it is placed as a mortar in the wall, it may take up water from the wall and make it loose cohesion. This is a phenomena that takes place specially in unstabilised rammed earth walls and it is attenuated in cement stabilised rammed earth walls.

Seeing this, in unstabilised rammed earth, it is commonly used clay or lime as a mortar and in stabilised rammed earth, depending on what compound was previously used on the building, the mixture for the binder will have a similar one.

These recommendation cannot be followed as a yardstick because every wall is different, therefore it is necessary to analyse each wall and its features to see which one is the best mortar.

The formwork

Now we have seen the properties of rammed earth, its advantages and weak points, we need to talk about how a wall made of rammed earth is build.

One of the reasons why rammed earth walls are one of the most ancient techniques of our civilisation is its simplicity of materials, such as soil which can be found anywhere and whatever you need for building an appropriate formwork. The formworks usually are made of wood but may be of other materials if necessary, but it's not a common practise.

For building a good formwork we need the typical tools for working with wood, not much more than a saw, a hammer and some nails.

The formwork usually consists in two parallel walls separated and interconnected by spacers. This spacers are as a rule made out of iron or steel because we need to be the most resistant piece of the formwork.

We have two types of formwork, the traditional block formwork which allow us to make a "small" block of rammed earth, which will be used as a huge brick if we compare it with current brick house building, and using the same formwork repeatedly we can build the whole structure, building block by block.

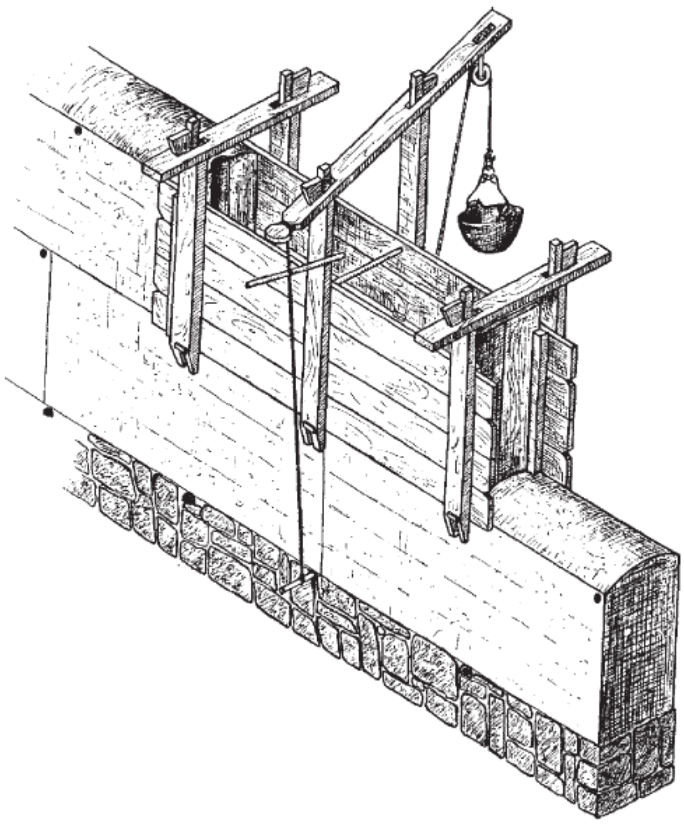

Figure 37: Scheme of a traditional rammed earth formwork. Source: *La técnica del tapial en la construcción tradicional de la provincia de Albacete*

In figure 37 we can see a traditional formwork made out of wood with the spacers maintaining the walls together. Can be appreciated that under the block in construction there is a layer of blocks already done and left to the block, a completed block is built, this one just finished.

This is how it works, we do the first block, then we move the formwork to one side and build the block next to the first, and so on until the first layer is done. When is finished, we start with the second layer, and then the third, until the wall is finished completely.

This is the traditional procedure. But in the figure 37 we can observe some curiosities, for example, below the first layer of rammed earth there is a layer of, in this case, stone with probably cement, this is usually done in order to protect the inferior layer of rammed earth from the water that could be on the ground floor in case of storm, water is the main problem when it concerns to durability of rammed earth, that's why we usually put a layer of any material which is not affected by water, nowadays usually is a brick layer with cement.

In the figure we can also see there is a pulley with a basket in the structure, the utility of this is for raising the soil from the ground level until wherever level we are when building, this is the easiest way to do it and the one that requires less machinery.

The traditional formwork has a small problem: the spacers. Once the block is done, when we remove the wood for preparing the next block, we also have to quit the spacers, this spacers will leave holes in the wall that have to be filled with ground (we do not want a wall with holes). This is not a major problem but, how good would be not having this holes?

In countries where the rammed earth construction is a very important issue are developing new ways of improving the traditional method, and one of the experiments consists in avoiding as much as possible this holes spacers create.

What workers try to do is to use as thinner spacers as they can but, the strength they have to support is very high. The Building Research Laboratory (BRL) has developed a new method to completely eliminate the spacers, shown in picture 38.

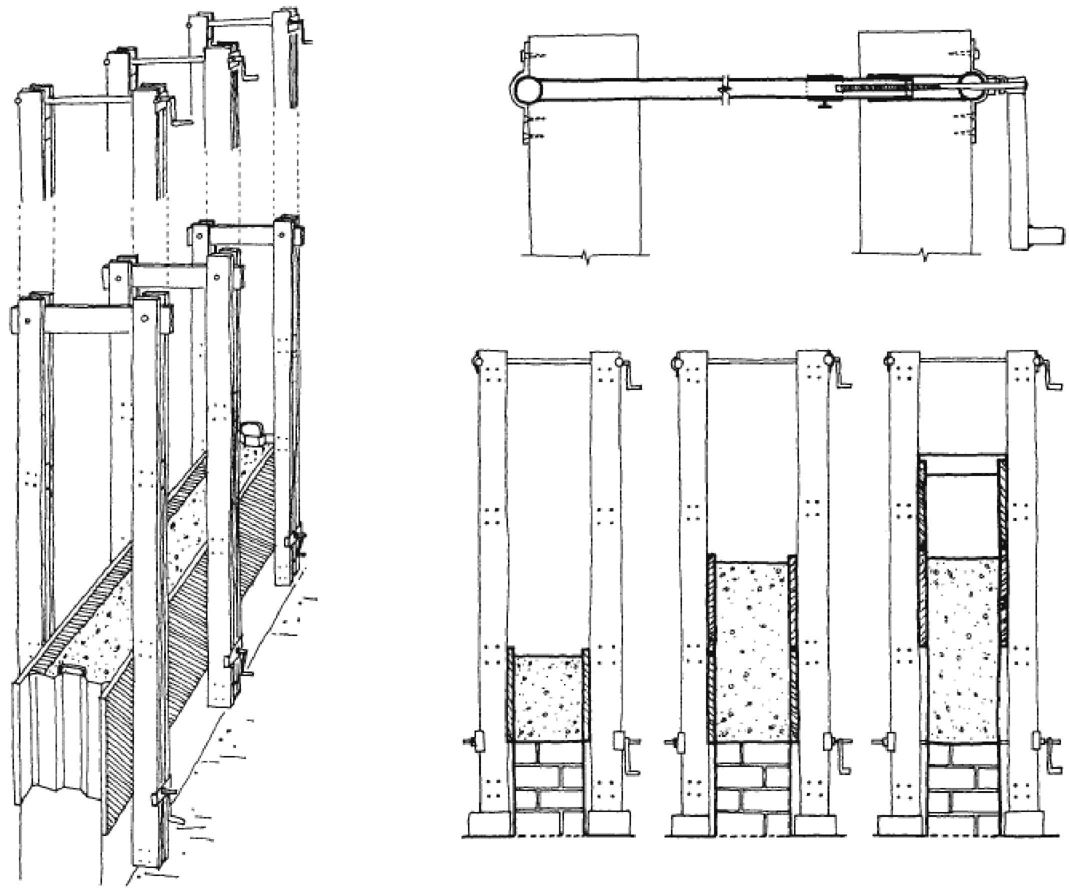

Figure 38: Sliding formwork for rammed earth panels. Source: *Building with earth Design and Technology of a Sustainable Architecture*

This method consists in several columns made out of steel or wood which will support the parallel walls, with a simple mechanism which will allow the panels of the formwork to be moved up as long as the layers are done.

This method has shown to be very good due to reduction of joints, shrinkage and we do not have the holes caused by the spacers. The first building made with this technique was done at University of Kassel (Germany) in 1982 rammed with a vibrator and the results were very good. The only disadvantage of this method is that it requires of a higher level of mechanisation so it is translated into a higher cost and the height of the wall is limited to the height of the columns that subject the panels.

Now we know how to build the quadrangular blocks, we should analyse how to make the corners of a building. There are two different methods, the traditional one and the most modern one.

The traditional has no mystery at all, is just the same procedure we would do with bricks, overlapping on each layer one belonging to a different directional wall, shown on the figure 39.

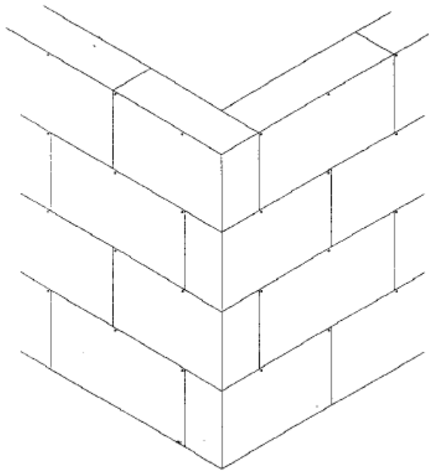

Figure 39: Scheme of a corner. Source: *La técnica tradicional del tapial*

This construction has the problem of very exposed joints in the corner and very near all of them. Over the years many different new formworks have been created with corner-shape in order to avoid this phenomena and do it in one simple step. I show a couple of solutions on the figure 40.:

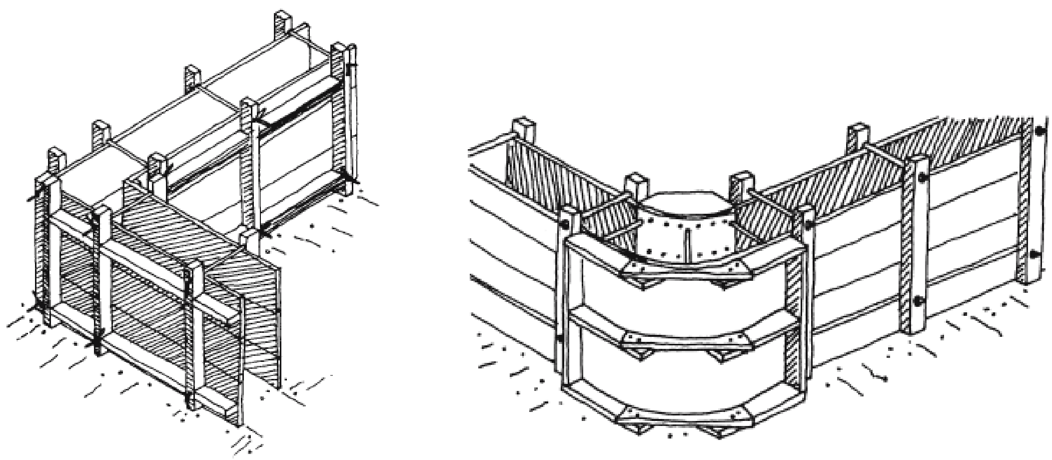

Figure 40: Corner formwork. Source: *Building with earth Design and Technology of a Sustainable Architecture*

One good property of wood is its ease for doing difficult shapes, that's why we always use it as a material for moulds and formworks for liquid materials such as concrete and this two different structures show two different shapes for a formwork in corners, the one in the left is more traditional with a 90 degree corner and the one in the right shows a smoothed shape on the corner, and both in one formwork, so it can be in one block the whole corner avoiding the issues mentioned before.

There is also another kind of formwork that is used for rammed earth. This kind is very actual because it requires heavy machinery, are the called "whole structures formworks".

This formworks have almost no differences with the traditional ones, are made of wood, may have spacers or not and the procedure once the formwork is placed is the same, the difference is that this ones are as big as the wall is, so for one wall, one formwork, once placed we throw soil inside, compact it and once compacted soil again. Repeating the process until roof and removing the formwork, we obtain a wall with no joints at all.

The problem with this formworks is that they are very huge and the setting up of the structure before starting with the earth and ramming takes a lot of time and resources, we may even need a crane. The good point is that when we retire the formwork the wall we obtain has almost no joints at all so it gains stability.

The same problem we have with the assembly is on the opposite way and if it is a monolithic piece this piece will not be useful anymore unless we decide to do an exactly equal wall or we modify the structure. An example of this kind of structures is shown in figure 41.

Figure 41: Huge formwork used in Wyoming (U.S.A.). Source: *Modern Earth Buildings materials, engineering, construction and applications*

As we can see in figure 41, the wall is already built and the formwork of this wall is being removed while the other walls of the structure have not been build yet.

In this big constructions usually we will need mechanical help for raising the soil from outside the formwork to the interior because doing it manually would be a major effort for workers so we usually use pulleys such as the one shown in the traditional formwork previously or we can have proper help if we use heavy-machinery such as a loader, just as shown in the figure 42 below.

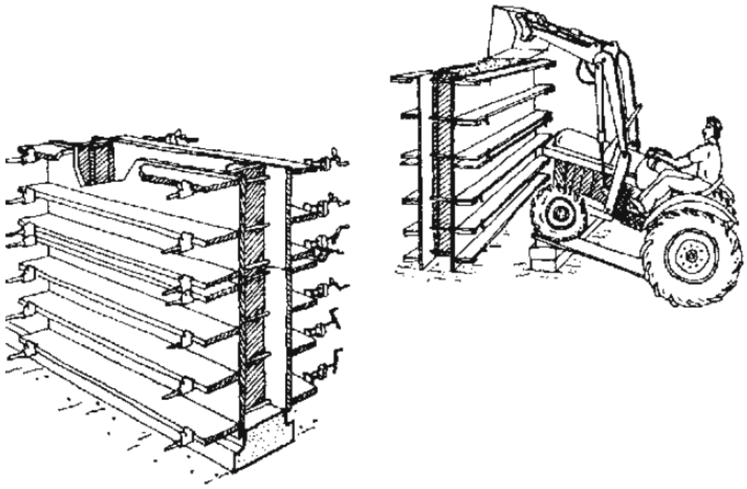

Figure 42: Filling a huge formwork. Source: *Building with earth Design and Technology of a Sustainable Architecture*

For using this filling method is no need to say that the formwork needs to be designed so the loader can do his job and the operator of the loader must be an experienced person because is a delicate job for such a powerful machine.

In this method, the workers that will compact the soil have to leave the structure before the loader throws the soil for safety reasons because death burial is one of the most important death reasons in construction.

Rams

When we talk about tools for rammed earth the basic tool is the rammer used for compaction. The classical rammer has conical, wedge-shaped or flat base.

If conical or wedge-shaped rams are used, the different layers are better mixed and provided there is sufficient moisture and a better bond is obtained. The problem is that this takes longer than ramming with a flat-base rams. Walls rammed with flat-based rams show less lateral shear resistance and therefore should be only loaded vertically.

The base of the ram should not be too sharp, so that the formwork is not damaged if it is made of timber. The base should not be smaller than $60\ cm^2$, and no larger than $200\ cm^2$. The weight of the ram should be between 5 and 9 kg. It is preferable to use a two-headed ram with a round head on one side and a square one on the other. This allows the ram to be used with the round side for general work, and with the square edge to compact corners effectively. A picture of a worker with this type of rammer is shown in figure 43.

Figure 43: Two-head ram used in Equador. Source: *Building with earth Design and Technology of a Sustainable Architecture*

Nowadays the use of electric and pneumatic rams is increasing, and there is a great variety of them when at frequency and diameter means. The problem is that the frequency uses to be very high for rammed earth constructions. The use of this pneumatic rams is mostly used when we have a huge construction due to the cost among other factors and the composition of the soil used may determine the special type of mechanic ram we need (number of cycles and frequency).

In the figure 44 is show the traditional shapes of rammers and some pneumatic ones. There is also shown a figure of a vibrator which may be used on sandy soils but not on clayey ones figure 45.

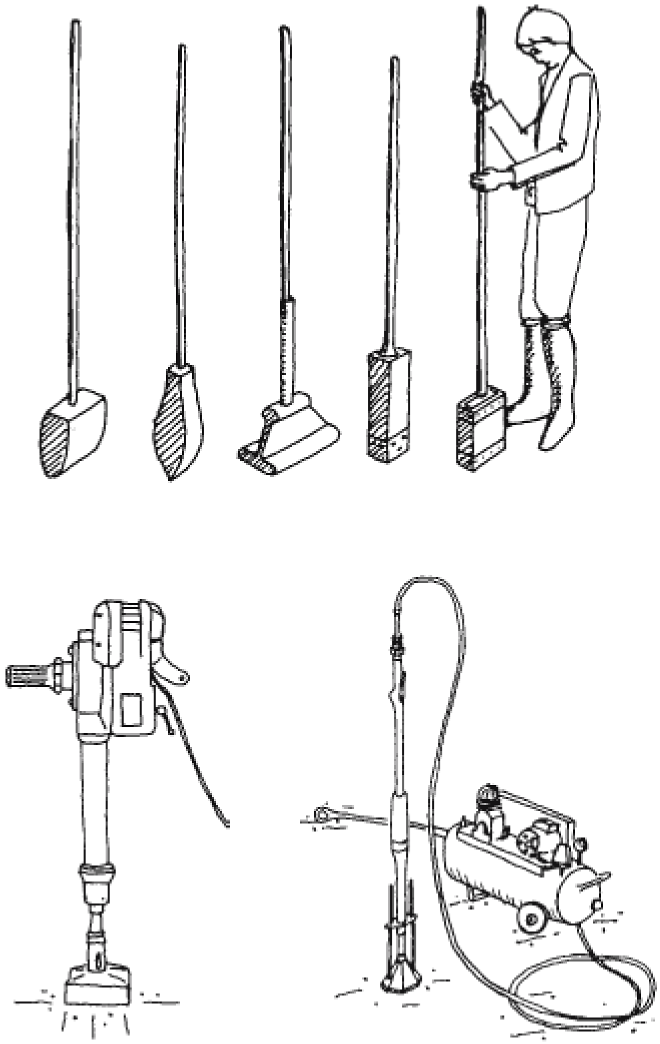

Figure 44: Different rams, manual above and mechanical below. Source: *Building with earth Design and Technology of a Sustainable Architecture*

Figure 45: Vibrating ram. Source: *Building with earth Design and Technology of a Sustainable Architecture*

Improving the traditional rammed earth to stabilised rammed earth

After seeing all the characteristics of rammed earth, we have seen that by adding some chemicals to the mixture, such as cement, we improve some of the properties of rammed earth, when we mix some additives in rammed earth construction, the resultant is known as Stabilised Rammed Earth (SRE).

There are various advantages of using cement as stabiliser. Soil samples gain strength from the formation of cement gel matrix that binds together the soil particles and the bonding on the surface-active particles, like clay within the soil. High levels of cement stabilisation improve the surface coating and reduce erosion while increasing the cement has a considerable influence in improving the resistance of soils vulnerable to frost attack [3].

Cement is typically used in proportions from 4% to 15% but the most common practises are between 6% and 10%. Increasing the amount of cement will make increase the strength but will make the earth less recyclable [3].

Now we are going to see, some examples of stabilised rammed earth experiments that have been done around the world with the objective of improve the characteristics of the materials, basically to strength and for avoiding as much as possible the weather erosion.

Durability experiment 1

The first experiment we will analyse was performed in Biskra University, Algeria and it was not made out with rammed earth but with loam unbaked bricks [8].

The project consisted in creating eight walls, using eight different stabilised bricks and then evaluating them under real climatic conditions. All eight walls were built with the same soil origin, tested by the laboratory in order to obtain all the properties I have explained previously in this work. In the figure 46 we can see the soil results:

Soil Characteristics

Constituents/ properties	Values	Constituents/ properties	Values
Textural composition, % by weight		Mineralogical constituents	
		Kaolin	45
Sand	64	Illites	40
Silt	18	Interstratifiers	15
Clay	18	Quartz	05
		Calcite	10
Atterberg limits		Physico-chemical characteristics	
Liquid limit, %	31		
Plastic limit, %	17	pH	7.1
Shrinkage limit	10	Methylene blue	0.2
Plasticity index, PI	14	Organic matter, %	0.15
Water content, %	9.5	Optimum (W_c), %	11.75
Activity coefficient	0.77	Max. dry density (γ), kg/m^3	1877
Product (PI × M)	644		

Figure 46: Soil characteristics table. Source: *Durability study of stabilized earth concrete under both laboratory and climatic conditions exposure.*

The additives used are:

Algerian cement, tested in laboratory after 28 days, whose strength was 46 MPa.

Standard lime

A resin, manufactured in Algeria, is an aqueous dispersion of resin of white colour, is compatible with most cements and also with lime. Its latex content is around 10% and 20% in respect to cement mass. This latex addition gives it a good adherence, impermeability and resistance to chemical attacks.

The eight different mixtures are:

Cement with two different contents: 5% and 8%

Lime with two different contents: 8% and 12%

Cement + lime with two different contents: cement 5% + lime 3% and cement 8% + lime 4%

Cement + resin with two different contents: cement 5% + 50% resin (of the compacting water weight) and cement 8% + resin 50%

The samples were prepared in a very standard way, so there is no need to explain it (very similar to the method explained for rammed earth samples). And then 8 different walls were built with the bricks and were left on a roof, so they were entirely exposed to all weather factors during 48 months (4 years).

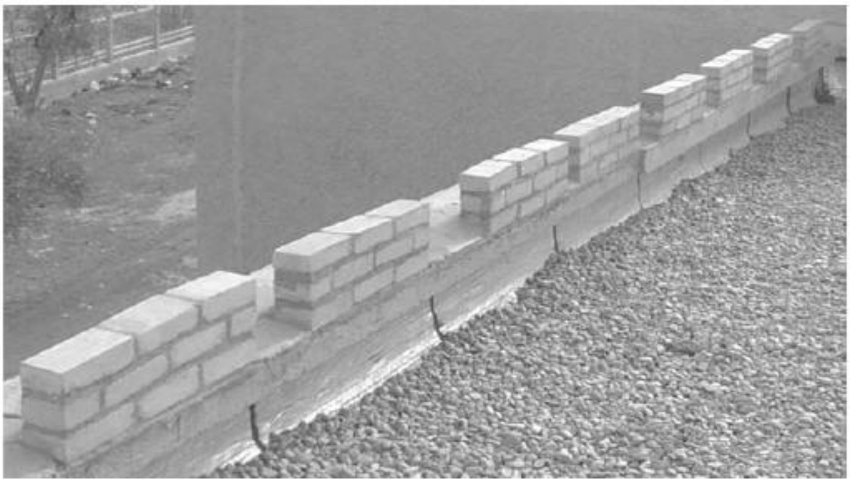

Figure 47: General view of the built walls. Source: *Durability study of stabilized earth concrete under both laboratory and climatic conditions exposure.*

After this four years, many laboratory tests were performed to the samples, most of them explained previously in this work, such as compressive strength, capillary absorption, freezing and thawing test, spray test, etc. The main results are shown in the figure 48:

Test results

Bricks characteristics	Different walls treatment							
	Cement (%)		lime (%)		Cement (%) + Lime (%)		Cement (%) + Resin (%)	
	5	8	8	12	5 + 3	8 + 4	5 + 50	8 + 50
Compressive strength in dry state, MPa	15.4	18.4	15.9	17.8	17.5	21.5	17.2	19.5
Compressive strength in wet state, MPa	9	12.7	10.1	11.7	12.3	15.6	11.5	14
Water strength coefficient	0.58	0.69	0.64	0.66	0.63	0.7	0.67	0.72
Capillary absorption, %	2.35	2.2	3.7	2.9	2.3	2	2.3	2.1
Total absorption, %	8.27	7.35	9.8	9.02	8.1	7.9	5.9	5.3
Weight loss (wet–dry), %	1.4	1.25	2.3	2.1	1.2	1.0	0.9	0.9
Weight loss (freezing and thawing), %	2.35	2.23	3.7	2.9	2.3	2.0	2.3	1.8
Hole depth, mm – After spray test	1.0	0.5	2.2	1.0	1.0	0.5	0.25	0.2
Hole depth, mm – Real life exposure	–	–	1.0	0.5	–	–	–	–

Figure 48: Results table. Source: *Durability study of stabilized earth concrete under both laboratory and climatic conditions exposure.*

As we can observe in this results, the compressive strength has very high values if we compare it with $0.5 - 1.5\ MPa$ we usually can obtain with unstabilised rammed earth. Also the other results regarding to resistance to environmental effects are a lot better, so we can conclude the durability improves considerably with the addition of stabilizers, and in this case, the best choice for durability is cement+resin and for strength cement+lime.

Durability experiment 2

The next experiment was performed by the French Scientific and Technical Building Center. In this experiment, 104 earthen wall specimens were built out of different characteristics and mixtures. Each one of the specimens was built on a concrete base with a bituminous layer in order to prevent water to rise by capillarity, the water content of the samples was around 10% and the formwork was 1000x400x1100 mm. All the specimens were protected from rainwater with an asbestos cement roof, and some reference walls were also built with no protections, other were painted or plasted. The procedure to rise the samples was not different to the standard one, but with no standardisation of the compacting force, it was manually done by a mason, judged by its experience [9].

The soil used was a local one, compacted in 150 mm layers and the three main mixtures used were:

MRE is a standard unstabilised rammed earth wall built with nearby soils

SMRE is a MRE rammed earth wall stabilised with 5% by dry weight of hydraulic lime.

FRE is an unstabilised rammed earth wall made with fine soil.

And after the samples were built, they were left to natural weathering for 20 years.

Figure 49: General view from the south of the walls on the site. Source: *Durability of rammed earth walls exposed 20 years to natural weathering*

This experiment was initially performed for the analysis of durability, so it is important not to damage the samples when analysing them, that is why an innovative method for testing the samples was developed: an stereo-photogrammetric method.

In this method, two photos taken from two different points of view are superimposed and then viewed with an stereoscope. The measurements on the pictures were accurate enough for the testing with a small deviation and the compare between the initial relief and the one taken 20 years later we can take some conclusions:

Even though this experiment has been performed during 20 years, has some limitations when referring to durability, here the walls have the two main surfaces exposed to weather when usually what we want is one exterior surface, so this means this walls are more affected than they should and this will alter the results.

In most of the walls, the upper part is less eroded and the reason is the roof. The protection the roofs are giving to the walls against rainwater is very high.

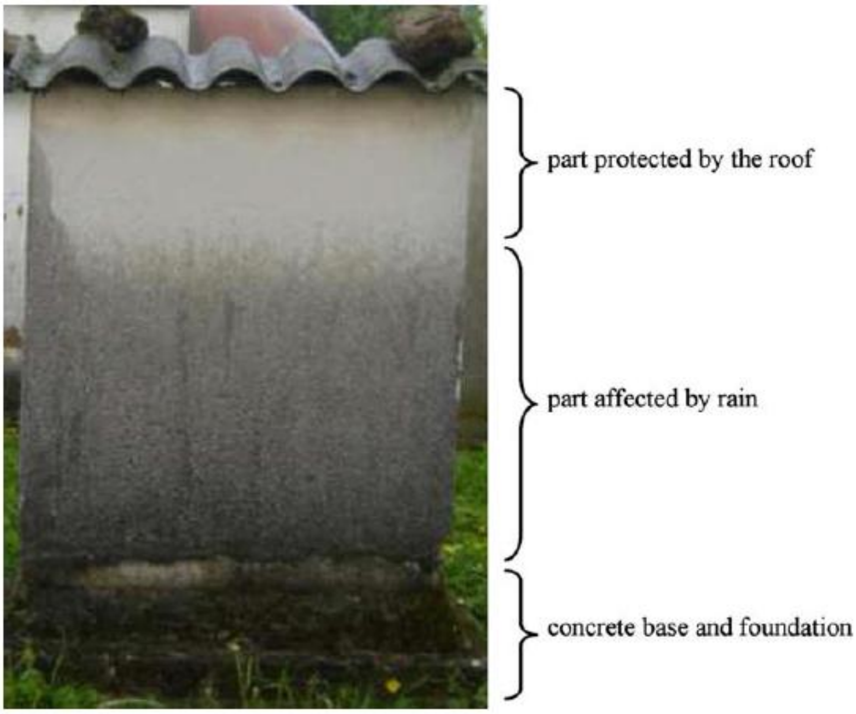

Figure 50: Photo of wall number 23 after the rain. Source: *Durability of rammed earth walls exposed 20 years to natural weathering*

Finally the results of erosion are the following:

MRE: erosion measurement about 6.4 mm (1.6% of wall thickness)

SMRE: erosion measurement about 2 mm (0.5% of wall thickness)

FRE: similar to MRE.

It has been observed also that the increase of the erosion depth is not linear in time, what is obvious if we directly relate it with the weather conditions which are absolutely unpredictable.

Some studies research have concluded that a rammed earth wall lifetime is until the erosion reaches the 5% of its thickness, due to the construction with high safety factor, so with the results obtained here, an extrapolation has been made and we can conclude that the unstabilised rammed earth walls can resist more or less 60 years whereas the stabilised ones may have a much longer life, even more than 100 years.

Despite the results, we can find around the world constructions made with rammed earth with hundreds of years with no stabilisation at all, so the experiments may not be absolutely determinant.

Strength experiment 1

Many are the experiments performed in order to determine how the resistance of rammed earth increases or not by adding cement to the mixture. In this typical experiment what is usually done is perform the samples without adding water and then add a certain percentage of mass of cement calculated as % of dry mass. After adding the cement and weighting it we add the water and we proceed as usual [10].

After the curing period, we test the samples.

The next table shows the results of a test performed in the University of Nottingham, in United Kingdom. This is a standard test on whom it has been used different percentages of the same cement, CEM IIa Portland Cement, and tested its strength. The optimum moisture water content was previously determined with a Proctor test.

	Soil component proportions (kg/kg 10)				OMC (% wt dry)	Dry density [ρ_d (kg/m^3)]	f_{cu}' (N/mm^2)
	Gravel	Sand	Silty clay	CEM IIa			
ρ_s (kg/m^3)	2.68	2.65	2.65	3.15	–	–	–
Mix							
433 (0%)	4	3	3	0.0	8	2167.6	0.67
433 (3%)	4	3	3	0.3	8	2142.6	3.26
433 (6%)	4	3	3	0.6	8	2124.0	3.51
433 (9%)	4	3	3	0.9	8	2177.0	6.99
613 (0%)	6	1	3	0.0	8	2167.0	1.74
613 (3%)	6	1	3	0.3	8	2153.0	2.11
613 (6%)	6	1	3	0.6	8	2124.0	4.99
613 (9%)	6	1	3	0.9	8	2106.2	4.78
703 (0%)	7	0	3	0.0	8	2085.3	1.77
703 (3%)	7	0	3	0.3	8	2052.5	3.22
703 (6%)	7	0	3	0.6	8	2073.6	3.27
703 (9%)	7	0	3	0.9	8	2104.1	4.64

Figure 51: Physical properties of stabilised earth mix designs. Source: *Influence of cementitious binder content on moisture transport in stabilized earth materials analyzed using 1-dimensional sharp wet front theory*

We can observe the results are getting better as we increase its percentage of cement while its dry density is not (there is an exception on the increase of resistance of the value 613 (6%) which resistance is higher than on 613 (9%), in the article is unexplained).

Strength experiment 2

As the experiment performed when the explanation of how to fabricate samples, and with its results, shown in figure 34, we can see which are the loams that resist more , depending only on its grain-size distribution. Now if we take the best results of unstabilised rammed earth samples, and we try to add cement to them to increase the resistance, we should obtain optimum strength for the structure.

This has been done in the University of Nottingham, UK, the same experiment on which I explained how to make samples but with that results, they added cement to the mixtures with higher resistance values, in this case, the samples:

613
433
703

And different values of cement:

0%
3%
6%
9%

The procedure is the same explained, so I will only show the results plotted on figure 52:

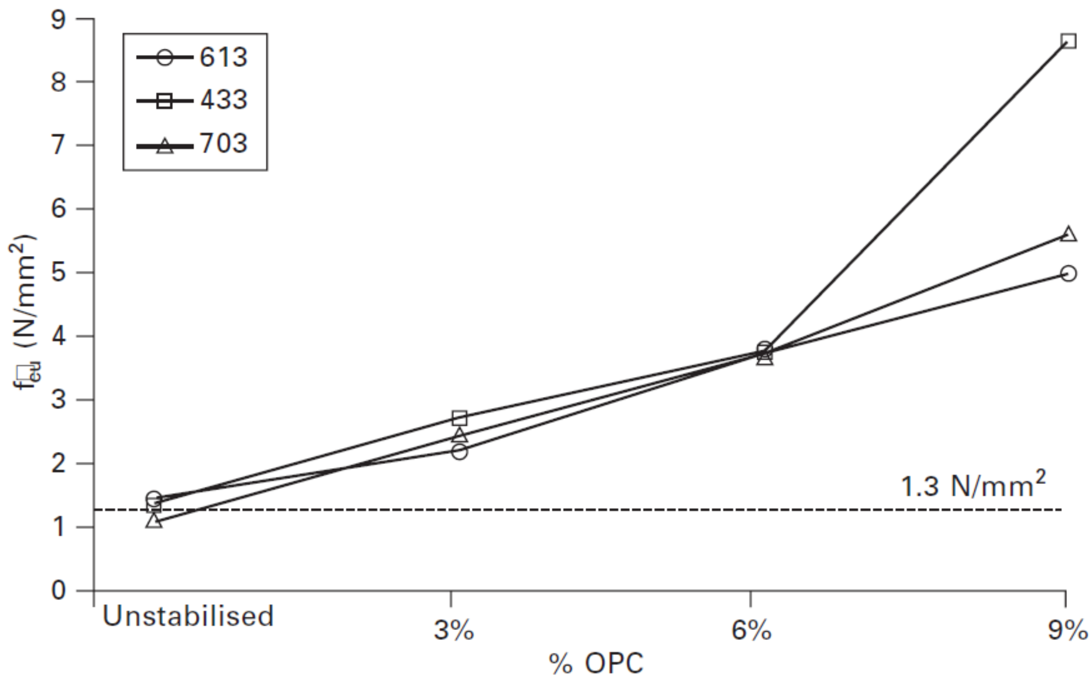

Figure 52: Relationship between cement content and compressive strength for the three different types of mixture. Source: *Modern Earth Buildings materials, engineering, construction and applications*

After the analysis of four different relevant articles of rammed earth experiments with different proportions of stabilisers just like the experiments previously explained of Biskra University, the French Scientific and Technical Building Center, and others, that will be listed afterwards, a table has been elaborated with the comparison of the results.

The results shown in figure 53 are very clear regarding one subject: with additives, rammed earth always gets more resistance. Depending on which additive, the proportion of it, and the presence of other substances, strength will be higher or lower.

As we can see in the results we can take several conclusions:

Cement and lime are the best additives that can be added to the mixture when it concerns to resistance. Flying ashes and others, like alginates, do have good results but, the percentage of them that is needed in order to achieve the same characteristic value of strength is significantly higher.

As it was previously explained, and as it is obvious, the same proportion of additive in different samples with different grain size distribution differs significantly.

The more additives we add, the higher resistance we obtain but, this implies always higher costs and the material obtained will be less recyclable, making some of strong points of building with rammed earth disappear.

Finally, the best results are when we use a combination between cement and lime, which are the results of the experiment number 2 in this table and also previously explained with more detail. So it is keen to think that for building structures, this is probably the ideal addition we should add, cement and lime.

Title of the article	Institution	Sample	Composition of the sample			Additive 1	% additive 1	Additive 2	% additive 2	Additive 3	% additive 3	Water content	Density g/cm^3	Compressive strength MPa	Flexural strength MPa	Notes
			Sand	Silt	Clay											
Clay-based composite stabilized with natural polymer and fibre	ETS Arquitectura de Sevilla	01 ERROL	18.0000	36.0000	25.6000	Alginate	-	Lignum	0.50	Wool	-	19.50	1.82	2.23	1.12	
		02 ERROL	17.8875	35.7750	25.4400		19.75		0.50		-	0.25	1.84	3.77	1.06	
		03 ERROL	17.8875	35.7750	25.4400		-		0.50		0.25	19.75	1.80	3.05	1.10	
		04 ERROL	17.7750	35.5500	25.2800		19.50		0.50		0.50	0.50	1.79	4.37	1.05	
		05 ERROL	17.8875	35.7750	25.4400		19.50		0.50		0.25	0.25	1.79	4.44	1.45	

Title of the article	Institution	Sample	Composition of the sample			Additive 1	% additive 1	Additive 2	% additive 2	Additive 3	% additive 3	Water content	Water strength coefficient	Compressive strength MPa	Notes
			Sand	Silt	Clay										
Durability study of stabilized earth concrete under both laboratory and climatic conditions exposure	Faculty of engineering, Biskra University, Algeria	Sample 1	64.0000	18.0000	18.0000	Cement	5.00	Lime	-	MEDALATEX percentage of the compacting water weight	-	OWC used	0.58	15.40	MEDALATEX is a resin provided by an Algerian company with 10-20% latex content
		Sample 2					8.00		-		-		0.69	18.40	
		Sample 3					-		8.00		-		0.64	15.90	
		Sample 4					-		12.00		-		0.66	17.80	
		Sample 5					5.00		3.00		-		0.63	17.50	
		Sample 6					8.00		4.00		-		0.70	21.50	
		Sample 7					5.00		-		50.00		0.67	17.20	
		Sample 8					8.00		-		50.00		0.72	19.50	

Title of the article	Institution	Sample	Composition of the sample			Gravel	Additive 1	% additive 1	Additive 2	% additive 2	Water content	Density g/cm^3	Compressive strength MPa	Notes
			Sand	Silt	Clay									
Rammed earth construction with granitic residual soils: The case study of Northern Portugal	Department of Civil Engineering, ISISE, University of Minho, Guimaraes, Portugal	S1	45.0000	14.0000	6.0000	35.0000	These are unstabilised rammed earth samples, so no additives are added				OWC used	1.92	0.41	The soil used in the stabilized samples has the same proportions as S3
		S2	59.0000	15.0000	5.0000	21.0000						1.84	0.25	
		S3	60.0000	14.0000	4.0000	22.0000						1.71	0.43	
		S4	53.0000	12.0000	12.0000	23.0000						2.01	0.41	
		GSRE 2.5	58.5000	13.6500	3.9000	21.4500	Fly ash provided by a Portuguese company	2.50	-			Non-specified	0.72	
		GSRE 5	57.0000	13.3000	3.8000	20.9000		5.00					0.93	
		GSRE 7.5	55.5000	12.9500	3.7000	20.3500		7.50					1.09	

Title of the article	Institution	Sample	Composition of the sample			Gravel	Additive 1	% additive 1	Additive 2	% additive 2	Water content	Density g/cm^3	Compressive strength MPa	Notes
			Sand	Silt	Clay									
Advances on the assessment of soil suitability for rammed earth	School of Civil and Resource Engineering, University of Western Australia, Australia	1	50.0000	25.0000	5.0000	20.0000	Cement	Unstabilised	Lime	Unstabilised	5.80	1.971	0.400	
		2	50.0000	0.0000	30.0000	20.0000					8.30	1.969	0.723	
		3	50.0000	15.0000	15.0000	20.0000					6.40	2.005	0.443	
		4	40.0000	20.0000	30.0000	10.0000					7.40	1.791	0.553	
		5	20.0000	20.0000	40.0000	20.0000					9.60	1.758	0.717	
		6	50.0000	15.0000	10.0000	25.0000		5.00		0.00	5.60	1.995	5.957	
		7	40.0000	5.0000	10.0000	45.0000		4.50		0.00	5.40	2.153	11.010	
		8	60.0000	0.0000	20.0000	20.0000		4.00		1.00	7.40	1.940	5.143	
		9	20.0000	10.0000	30.0000	40.0000		4.00		2.00	9.40	1.793	3.450	
		10	50.0000	25.0000	5.0000	20.0000		4.50		0.00	5.30	2.007	7.790	

Figure 53: Table with the results of 4 different experiments regarding rammed earth resistance.

After explaining what the experiments say it is best, what it is used in construction world?

In building sector, prices are determinant so, if in an specific area, price of lime is significantly lower than cement one, probably lime will be used and the same situation would we have if cement price is the lowest.

In countries like Spain, where the price difference between cement and lime is almost zero, constructors base its decision of using one or the other on its experience or on the amount needed to achieve the same strength. As shown in the table, for achieving the same resistance, the best option is adding cement, the more cement, the higher resistance.

Depending on the soil, lime will work better than cement but, usually cement works better as stabiliser so that is why is the most used around the world.

In construction world, the percentages of cement used are between 5% and 10%, depending on the structure but, there are also buildings with less content, even in some cases with no additives, depending on the zone and the use that is going to have the structure.

In Spain we have hundreds of houses built with unstabilised rammed earth around the territory and also some castles or forts atop hills, just like Alhambra, in Granada, one of the biggest and most famous castles in Spain.

Codes and legislation about rammed earth construction

As said previously, is difficult to create an international document about earth building due to the different soils and composition around the world and the climate difference, which would make different building structure.

There are but, some national codes, from those countries where rammed earth use is very extended through its territory. Some of them are Australia, Germany, New Zealand and Spain.

In this standards the treated aspects are the ones we have previously mentioned, such as durability, plasticity of loam, unconfined compressive strength, etc. What is generally given is a recommendation for the construction and in many cases standardisation of laboratory tests, such as how to make samples or which type of correlation has to be used for the results.

The Australian Earth Building Handbook details the materials and techniques available for earthen construction, advices on detailing, construction and maintenance. It also speaks about the requirements of an earthen wall regarding durability and structural integrity and provides guidelines for the effective design of reinforced and unreinforced earth walls. [3]

The German standard treats the general requirements of earthen construction, the types of suitable soil, the methods and procedures to construction and finally properties and how to check them about earthen structures [3].

New Zealand's legislation is divided on different parts, depending on the height of the structure that has to be built. The specifications of the legislation is the same as in the previous ones mentioned but with more detail regarding to its particular conditions.

In all the different codes we can see that all the properties given are always recommendations, so if the designer of the structure does not want to respect the rules, as long as it is justified, can do the structure however he wants.

Nowadays new codes and standards are being developed due to the increasing use of rammed earth construction, this will help the extension of the use even more and will allow us to have a specific standardisation of the techniques for testing the rammed earth because most of the techniques we use are developed just for soil, concrete or others and we have no perfect accuracy [2].

Rammed earth structures around the world

As we have seen, the construction with rammed earth is very extended throughout the world. In order to proof it, an example of a construction in each continent will be shown.

House in New Zealand

As previously said, Australia and New Zealand are two of the countries where earth construction is more extended. This house is an example of this kind of construction.

Figure 54: Example of rammed earth construction in New Zealand. Source: http://www.earthhomes.co.nz/Portfolio.html

Mangar Hotel in India

Located in New Delhi, a zone whose temperatures can reach easily 50ºC, the construction of a rammed earth building maintains the temperature on the inside of the building in good values.

Figure 55: Mangar Hotel in India. Source: http://www.sirewall.com/portfolio/commercial-projects/mangar-hotel/

Sankofa house in Ghana

A familiar house built in Ghana, a country whose temperatures can reach 40ºC and has to resist the raining period with until 2000 mm of rain.

Figure 56: Sankofa house in Ghana. Source: http://eartharchitecture.org/index.php?/categories/10-Africa

Palace in France, Dauphiné - Château, from 19th century

This palace in situated in France and has more than a hundred years, the construction is worth to be seen.

Figure 57: Palace in France, Dauphiné - Château. Source: http://www.earth-auroville.com/traditional_rammed_earth_en.php

Grand Beach washrooms, Manitoba, Canada.

This is the most extreme case I found, located in a place that can reach up to 40ºC in summer and -50ºC in winter, a temperature difference of 90ºC, public washrooms in the beach. The structure has suffer no damage.

Figure 58: Grand Beach washrooms, Manitoba. Source: http://www.sirewall.com/portfolio/commercial-projects/grand-beach-washrooms/

After seeing all this constructions around the world and as previously seen, the legislation codes in different countries we shall analyse how the distribution of building is organised throughout the globe.

The countries in where the rammed earth is gaining popularity are basically: Germany, Australia, New Zealand, Spain, United Kingdom, Brazil, India, Algeria, Egypt and many other African countries. What do these countries have in common?

The answer is simple, if we want to join all these countries, we will have to split them in groups, we cannot gather in the same category Germany and Algeria, as example.

Regarding the countries mentioned before, we may split them in two different groups, the first of which would be composed by the "1st-world ones", such as Germany, United Kingdom, Australia, New Zealand and Spain and the other group would be the result of gathering the rest of them.

If we try to look similarities among these groups and differences between them it will be an easier task, and now let's try to see why rammed earth construction is increasing in both of this groups.

If we first have a look at the group composed by Germany and Australia, we should ask ourselves why rammed earth is gaining popularity. The answer is not trivial because in this countries building with "better" materials is already extended, concrete and baked bricks are the main materials in building and when to strength and properties is concerned, they are clearly better and they are cheap enough so everybody can afford to buy a home built with them. Why then returning to classical building methods, after all the improve that has been done in the last decades?

As previously explained, building with earth is not only cheaper but also eco-friendly, it does not resist enough for building a structure of 20 floors, such as concrete, but it will work as house for individuals, so individuals with ecological mentality and with money enough will have a house built with this method in order to reduce pollution. It is possible that building a house with rammed earth in one of this countries is not going to be as cheaper as expected due to the lack of professionals in this sector and its high salaries, it is probably not going to be possible to build a house in the middle of a big city because of the field price and the legislation on this constructions is, as previously explained, not determinant.

If all this problems are avoided, a house can be built respecting the environment and taking benefit of all properties that earth building comes with.

So in these "developed" countries, the tendency is to move from concrete buildings to ecological ones, which in many occasions are not in the centre of the city but in the outskirts or directly on the field.

In the second group of countries mentioned before, whose main participants are India, Brazil and African countries in general, the tendency is quite the opposite.

In these countries the most important characteristic that is making the construction with earth successful is neither its resistance, nor its eco-friendly properties, is the fact that is a self-building material, cheap and the ease of finding adequate materials for building.

In these poor countries, people usually does not have money to afford buying a new house, so its solution is easy, they build it themselves. Usually people gathers together and during several days in groups of 10-15 people, they can build a house. There is no need of an expert engineer for the houses they are used to build because usually are 4 rigid walls and a simple ceiling. The material necessary for the construction is "free" because it is just soil, that can be found anywhere, and the formwork can be used for building dozens of houses. That is why an entire village gathers together once a week for building between them a house for one family and when the house is finished, they start doing another for another family, and then another, and another.

This cheap way of construction is why it is said that with earth building, a man cannot build a house, but 10 men can build 10 houses.

So, in these "poor" countries, where a home can be something hard to find or pay, these teams of voluntary people, help others to have a place to live in, not a very glamorous house probably, but good enough to live.

There is but, something that totally differs from what happens in "rich" countries: people are tending to move from these houses made with earth to ones made out of concrete or brick. It is radically different of what was explained before, that the tendency of countries like Germany is to go to eco-housing, these other countries tend to go in the opposite way, just because its social impact.

It may seem strange, but in many countries saying you live in a house made of earth, sounds like unpopular, like a person with no resources, just the opposite that would happen in a country like, for example Canada.

This is why people in countries like India, who already have a good house made with rammed earth, with very good properties, as explained before, when to hot temperatures refer, especially in a very hot climate, prefer to move to a concrete or brick house, with will perform much worst against these atmospheric situations, only because of the social reputation, exactly the opposite that happens in other communities.

Summing up, in developed countries, the return to the earthen houses is the new trend whereas in countries under development where there are few resources and people live in earthen houses because it is the only method for building houses available, as soon as they can, they leave this buildings towards concrete ones.

There is a new trend nowadays, whether in rich countries or poor ones that is modern arquitecture for tourism, such as the picture shown in figure 55, a hotel in India, only for tourists that want to feel like locals and stay in a typical house as the ones in the area. The point of this is showing how people there live but, the quality is significantly better than the real ones, built, probably as explained before, by a group of people, with no experts.

Environmental impact

After seeing the whole process of how are rammed earth structures built, we can understand why is it called an eco-friendly material and also very cheap for building.

The process of rammed earth building can be summarised in 4 steps:

1: Excavation for obtaining the soil

2: Preparation of the mixture

3: Insertion of the mixture on the formwork

4: Compaction

If we compare it with other different methods for building, for example brick housing, summarised steps would be:

1: Obtainment materials

2: Transport to the factory (optional, factories can be placed just aside the sources)

3: Industrial process: mixture, moulded, baking, cooled

4: Transport to the building site

5: Building

Or for example concrete construction:

1: Obtainment material

2: Transport to the factory (optional, factories can be placed just aside the sources)

3: Industrial process: mixture into a truck mixer

4: Transport to the building site

5: Insertion of the concrete into the mould

6: Drying process

If we compare this methods, there are two similarities between concrete process and brick one and at the same time, this similarities do not appear in rammed earth construction. We are referring to:

Transport

Industrial process

In both cases we have the factor transport, that is not mentioned in rammed earth process, that is one of the reasons why rammed earth is less-pollutant than other methods, the material used in the construction is placed in-situ. This may seem no sense but, costs derived from transport cannot be obviate and neither can be the pollution caused by them.

The other important factor is the industrial process mentioned. The complexity of the process is not relevant now but the energy used and the costs that it produces are a major issue, especially in the case of brick factories, where the brick has to be baked. The industrial process of concrete may not require that amount of energy but, the reaction of cement when it mixes with water, produces a non-trivial amount of CO_2. This gas is the pollutant par excellence, in fact, the measure for pollution is measured in CO_2, so it makes it easy to compare the amount of pollution created by of this methods, as it is shown on the figure 59:

Material	**Density** $\boldsymbol{kg/m^3}$	**Emissions per Kg** $\boldsymbol{kg\ of\ CO_2/kg}$	**Emissions per** $\boldsymbol{m^3}$ $\boldsymbol{kg\ of\ CO_2/m^3}$
Rammed earth	2200	0.004	9.7
Adobe	1200	0.06	74
Concrete	2360	0.14	320
Prefabricated concrete 2% steel	2500	0.18	455
Massive brick	1600	0.19	301
Hollow brick	670	0.14	95

Figure 59: Emissions of CO_2 of different materials. Source: *Earthen construction in the 21st century. S. Bestraten.*

The results shown in figure 59 speak for themselves, the amount of CO_2 produced by bricks or concrete are more less similar whereas the amount produced by rammed earth are insignificant in compare.

It is necessary to say that when we refer to stabilised rammed earth with cement, the amount of CO_2 is increased by a 150% but, this is still far away from the pollution of usual materials.

Conclusions

After all seen in this project, I have arrived to several conclusions:

Earth building techniques are very important in today's world, due to many factors, such as its properties, its reduced costs and the factor of zero-transport of material that gives us a very strong point for reducing the necessary energy for building structures, what is very beneficent for the environment.

Among all earth techniques, rammed earth shows better properties, improved strength due to the ramming process and the options of improving it even more with additives such as cement as shown.

The properties of earth materials, particularly mixture's are easy to compute and its interpretation is, in most cases, intuitive. With the laboratory tests and the field ones, we can achieve good enough conditions for building a rammed earth structure that will be able to resist many years.

We have seen that the benefits that building with earth provides are excellent for health and comfort and that is why I personally think that this technique should continue its extension throughout the world, but not only among "poor" people as it is in undeveloped countries, where earth is the building material because they have nothing better, it should be extended to everyone, as it is starting to happen.

The legislation of earth techniques is mostly under development but advanced countries are realising that is an important construction method and they are developing new codes, that is what should be.

Finally saying that with new experiments and research we can achieve to build fantastic buildings with such a simple technique and this means nobody knows which and where is the future of this building technique.

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